Analytical model development for the prediction of the frictional resistance of a capsule endoscope inside an intestine

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Abstract: For the purpose of optimizing the design of the locomotion mechanism as well as the body shape of a self-propelled capsule endoscope, an analytical model for the prediction of frictional resistance of the capsule moving inside the small intestine was first developed. The model was developed by considering the contact geometry and viscoelasticity of the intestine, based on the experimental investigations on the material properties of the intestine and the friction of the capsule inside the small intestine. In order to verify the model and to investigate the distributions of various stress components applied to the capsule, finite element (FE) analyses were carried out. The comparison of the frictional resistance between the predicted and the experimental values suggested that the proposed model could predict the frictional force of the capsule with reasonable accuracy. Also, the FE analysis results of various stress components revealed the stress relaxation of the intestine and explained that such stress relaxation characteristics of the intestine resulted in lower frictional force as the speed of the capsule decreased. These results suggested that the frontal shape of the capsule was critical to the design of the capsule with desired frictional performance. It was shown that the proposed model can provide quantitative estimation of the frictional resistance of the capsule under various moving conditions inside the intestine. The model is expected to be useful in the design optimization of the capsule locomotion inside the intestine.

Keywords: biotribology, finite element analysis, frictional resistance, small intestine, viscoelasticity

1 INTRODUCTION

The development of a capsule endoscope has resulted in great progress in the field of medical surgery, especially in minimally invasive surgery [1, 2]. Recently, as further steps are taken in the technology, various efforts to develop a self-propelled robotic endoscope have been made [3–5]. Unlike the commercialized capsule endoscopes that move passively with the aid of peristalsis, a self-propelled capsule endoscope can control position, speed, and moving direction for itself and so it is expected that sampling, imaging, and even injection of medicine for specific regions will be achieved by the capsule endoscope.

Various locomotion mechanisms and propulsion systems using diverse actuators such as a magnetic motor, step motor, and spiral grooved impeller have been suggested for the self-propelled endoscope [2, 6, 7]. For such designs of the locomotion mechanism and propulsion system as well as the geometrical shape of the endoscope, fundamental understanding of the viscoelastic characteristics of the internal organs and the frictional resistance of the endoscope inside the body are definitely necessary since the power consumption and position control of the endoscope are largely affected by these characteristics [3–5]. However, because of many concerns such as cost and safety, it is hard to perform experimental investigations inside the body whenever the
data are required for the endoscope design. Based on these motivations, the objective of this research is to establish an analytical model for prediction of the frictional resistance of the capsule endoscope moving inside the body.

Figure 1 illustrates the process for the model development 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 various parameters can be collected. Also, the viscoelasticity test provides important information on the stress–strain relationship and the stress relaxation characteristics of the internal organs, which influences the frictional resistance. These experimental investigations in combination with the analysis of the capsule geometry effect make it possible to establish an analytical model for frictional resistance prediction.

Experiments performed prior to this work [8, 9] have revealed that the smooth cylindrical capsule shape showed the least frictional resistance and the friction coefficient of the capsule dummies moving inside the small intestine of a pig varied from 0.08 to 0.2. In addition, a viscoelasticity model, which consisted of five spring–dashpot elements, was suggested for the stress relaxation characteristics of the small intestine of a pig. Therefore, based on such experimental results, this work focuses on the development of a prediction model for the frictional resistance of a capsule moving inside the small intestine and its verification using finite element (FE) analysis. The frictional forces obtained from the prediction model and FE analysis were compared with the experimental results. The following sections describe the details of the model development.

2 MODEL ESTABLISHMENT FOR THE FRICTIONAL RESISTANCE OF A CAPSULE

When a capsule moves inside the small intestine of the body, various forces are applied to the capsule and the intestine. As a result, the frictional force of the capsule $F$ can be expressed as a sum of the components according to

$$F = F_W + F_S + F_P$$

where $F_W$ is the frictional force related to the capsule weight, $F_S$ is the frictional force induced by the stress due to the viscoelastic deformation of the intestine wall, and $F_P$ is the frictional force induced by the stress due to the peristalsis movement of the intestine. In this work, the friction component $F_P$ due to the peristalsis movement was not considered in the prediction model. As mentioned above, since the frictional resistance of a capsule was obtained by *in-vitro* measurement, there was no stress applied to the capsule by the peristalsis of the small intestine and the stress induced by the expansion of the intestine due to capsule insertion mainly affected the frictional resistance of a capsule. However, in

![Fig. 1 Analytical model development for the prediction of frictional resistance of a capsule endoscope moving inside the body](image-url)
order to estimate the actual frictional resistance of a capsule moving inside the body, the stress and the frictional resistance due to the peristalsis should be considered.

2.1 Stress distribution and frictional resistance analyses

2.1.1 Deformation of the small intestine

First of all, in order to analyse the stress and normal force applied to a capsule moving inside the intestine, the analysis and understanding of deformation of the intestine wall induced by the capsule are needed.

Figure 2 illustrates the deformation of the small intestine when a smooth cylindrical capsule endoscope is inserted. As the deformed shapes of the intestine wall were different according to local regions owing to the capsule shape, the capsule surface was divided into three sections as shown in the figure.

Sections A and C are the front and rear fillet parts respectively of the capsule, and section B is the midpart of the capsule. For the model development, the following assumptions were made.

1. The small intestine consists of an isotropic material and deforms symmetrically towards its radial direction.

2. There is no change in the volume and the wall thickness of the intestine after deformation.

3. The deformed shape of the intestine is identical with the external shape of the contact region of the capsule.

Based on these assumptions, the deformation of each part could be derived using the contact geometry between the intestine and the capsule.

2.1.2 Stress and frictional force of a capsule

In order to analyse the stress applied to the small intestine induced by capsule insertion, the concept of a pressure vessel [10, 11] was introduced as presented in Fig. 3. Referring to Fig. 3, the relationship between the pressure \( q(x) \) and the hoop stress \( \sigma_h(x) \) could be expressed as

\[
q(x) = \frac{\sigma_h(x)2\lambda(x)}{D_i(x)}
\]  

(2)

where \( D_i(x) \) and \( \lambda(x) \) are the inner diameter and the wall thickness of the pressure vessel at position \( x \) along the length of the intestine respectively. In the experimental work that was performed prior to this work, a model for the hoop stress of the small

![Fig. 2 Schematic diagram of the small intestine deformation after the insertion of a smooth cylindrical capsule.](image-url)
The moving speed and position, this equation can be and, for section C written as a function of the position at the time $t$

springs, and section can be expressed as of the capsule can be expressed as, for section A contact pressure

$\text{relaxation test}$ [9] according to

$$\sigma_b(t) = \varepsilon(t) \left[ E_1 \exp\left(-\frac{tE_1}{\eta_1}\right) + E_2 \exp\left(-\frac{tE_2}{\eta_2}\right) + E_3 \right]$$

(3)

where $E_1$, $E_2$, and $E_3$ indicate the elastic moduli of springs, and $\eta_1$ and $\eta_2$ are the viscosities of the dash-pots. Also, $\varepsilon(t)$ is the strain applied to the intestine at the time $t$. By using the relationship between the moving speed and position, this equation can be written as a function of the position $x$ according to

$$\sigma_b(x) = \varepsilon(t) \left[ E_1 \exp\left(-\frac{xE_1}{\eta_1}\right) + E_2 \exp\left(-\frac{xE_2}{\eta_2}\right) + E_3 \right]$$

(4)

where $v$ is the moving speed.

It should be noted that, since the strains and stresses of the intestine induced by the capsule are different at each section of the capsule shown in Fig. 2, the frictional forces at each section are also different.

First, in section B of the capsule, the hoop strain $\varepsilon_B$, the wall thickness $h_B$, and the inner diameter $D_{Ib}$ of the small intestine are constant. Therefore, the contact pressure $q_B$ and the frictional force $F_B$ of this section can be expressed as

$$q_B(x) = \frac{E_1 \exp(-xE_1/(v\eta_1)) + E_2 \exp(-xE_2/(v\eta_2)) + E_3 \cdot 2h_B}{D_{Ib}}$$

(5)

$$F_B = \mu \pi \int_B q_B(x)D_{Ib} \, dx$$

(6)

where $\mu$ is the friction coefficient.

On the other hand, in sections A and C, the hoop strains of the small intestine change according to time and position. Consequently, the hoop strains with respect to time or position should be defined first according to

$$\varepsilon_{A,C}(x) = \frac{D_{mA,C}(x) - D_{mb}}{D_{mb}}$$

(7)

where $D_{mA,C}(x)$ indicates the mean diameters of the intestine in section A or C at position $x$. In these sections, not only the mean diameter but also the inner diameter and the wall thickness are functions of the position $x$. Therefore, the contact pressures in sections A and C are

$$q_{A,C}(x) = \frac{E_1 \exp(-xE_1/(v\eta_1)) + E_2 \exp(-xE_2/(v\eta_2)) + E_3 \cdot 2h_{A,C}(x)}{D_{IAC}(x)}$$

(8)

Since the contact pressures $q_{A,C}(x)$ always act in the normal direction to each contact surface as shown in Fig. 2, the resisting forces per unit area in the $x$ direction generated by $q_A(x)$ and $q_C(x)$ can be described as, for section A

$$p_A(x) = q_A(x) \sin \theta_A + \mu q_A(x) \cos \theta_A$$

(9)

and, for section C

$$p_C(x) = -q_C(x) \sin \theta_C + \mu q_C(x) \cos \theta_C$$

(10)

Regarding these equations, an interesting point to note is that the resisting force in section C actually acts as a propulsion force to help the advance of the capsule, unlike in the case of section A.

The contact surface areas in these sections can be obtained by using the functions $g_{A,C}(x)$ for the geometrical shapes of the contact surfaces in sections A and C and are

$$S_{A,C} = 2\pi \int_{A,C} g_{A,C}(x) \sqrt{1 + [g'_{A,C}(x)]^2} \, dx$$

(11)

Therefore, the frictional forces in sections A and C of the capsule can be expressed as, for section A

$$F_A = 2\pi \int_A p_A(x)g_A(x) \sqrt{1 + [g_A(x)]^2} \, dx$$

(12)

and, for section C

$$F_C = 2\pi \int_C p_C(x)g_C(x) \sqrt{1 + [g_C(x)]^2} \, dx$$

(13)
2.2 Analysis of the frictional resistance component induced by the capsule weight

In addition to the effect of the geometry of the inserted capsule on the frictional resistance described in the above section, the effect of the capsule weight should also be considered. The weight of a capsule can deform the intestine and so it can add the hoop stress as well as the normal force to the intestine.

The weight and projected area of the aluminium capsule dummy with 10 mm diameter and 20 mm length, which were quite similar to the dimensions of the commercialized capsule endoscopes, were about 40 mN and 160 mm² respectively. Therefore, the hoop stress due to the capsule weight calculated using equation (2) was about 0.44 kPa. Figure 4 presents the strain of the small intestine of a pig measured by applying a constant stress, namely the result of the creep test. From the figure, it is found that the strain of 0.44 kPa will be less than 0.02 and so the hoop strain due to the capsule weight can be neglected. Consequently, it can be concluded that the proposed prediction model developed from the geometrical viewpoint is reasonable.

\[ F_w = \mu q_w \pi D_i L \]

\[ (14) \]

On the other hand, the capsule weight can affect the frictional resistance of the capsule directly because it adds normal pressure to the contact surface. On the assumption that only the lower half of the cross-section of the intestine supports the capsule weight, the frictional force component due to the capsule weight can be calculated by the equation

\[ F_w = \frac{\mu q_w \pi D_i L}{2} \]

where \( q_w \) is the contact stress due to capsule weight and \( L \) is the length of the capsule region which is in contact with the small intestine surface.

2.3 Comparison of the frictional forces between the prediction and the experiment

By using the model and the prediction process described so far, an attempt to predict the frictional force for capsules of various sizes with respect to the moving speed was made. Table 1 shows the frictional forces of the capsules calculated by the proposed prediction model. These predicted results were compared with the experimental values as presented in Fig. 5. The predicted frictional forces were similar to the experimental results, especially for cases where the diameter of the capsule was sufficiently larger than that of the small intestine. This may be because, in the case of the capsule with a small diameter, the intestine wall does not fit tightly around the perimeter of the capsule. In the experiment with small capsules, the soft and flexible intestine wall tends to droop and this interferes with the movement of the capsule. As a result, higher frictional resistance than the predicted value may be obtained.

As for the key parameters that have significant influence on the sensitivity of the proposed analytical model, the model is primarily based on the hoop stress distribution, the friction coefficient, and the
3 FINITE ELEMENT ANALYSIS OF THE FRICTIONAL RESISTANCE OF A CAPSULE

So far, the prediction technique for the frictional resistance of a capsule moving inside the small intestine has been developed by modelling the intestine as a pressure vessel from the biomechanical viewpoint. As a method to verify the validity and accuracy of the prediction model, an FE analysis using ABAQUS [12] was performed. The results from the FE analysis were also compared with those from the experiments and the predictions.

3.1 Model system configuration

For the FE analysis, a capsule and the small intestine were modelled as a two-dimensional axisymmetric structure, as shown in Fig. 6. The small intestine was modelled as a viscoelastic deformable body with the shape of a tube that has the average dimensions of a pig given in the footnote to Table 1. As for the viscoelastic material properties of the small intestine, the stress relaxation data that were expressed as equation (3) were used. The capsule was modelled as a rigid body and a smooth cylinder with a diameter of 10 mm and a length of 20 mm, which were similar to those of commercialized endoscopes.

As the boundary conditions for the analysis, both ends of the intestine were fixed in order not to rotate or move towards any direction. In the simulation, the travelling distance of the capsule inside the intestine was set to 50 mm with the speed range of 0.16–0.5 mm/s, which was the same as the experiment.

3.2 FE results and discussion

Figure 7 shows the distributions of various stress components that are applied along the capsule with a speed of 0.5 mm/s moving inside the intestine. First of all, from the von Mises stress distribution shown in Fig. 7(a), it can be found that a high stress is created in the region of the intestine wall that is
Fig. 7  Stress distributions applied along the capsule moving inside the small intestine with a speed of 0.5 mm/s obtained by an FE analysis: (a) von Mises stress; (b) hoop stress; (c) radial stress; (d) shear stress
in contact with the front of the capsule and the stress decreases towards the rear of the capsule owing to the stress relaxation characteristics of the small intestine expressed as equation (3) presented previously.

Figures 7(b) and (c) show the hoop stress and the radial stress respectively generated in the intestine wall. The hoop stress decreased along the capsule and the magnitude of the radial compressive stress was lower at the rear section than at the front section of the capsule. Therefore, such stress relaxation characteristics of the intestine lead to lower frictional force as the moving speed of the capsule decreases, as plotted in Fig. 5. These results also suggest that the front shape of the capsule is critical to the design of the capsule with desired frictional performance. However, the compressive radial stress may be neglected since the intestine is very soft and its internal structures such as villi and plicae show a cushioning effect.

On the other hand, the shear stress distribution of the small intestine, which is directly related to the frictional resistance of the capsule, is illustrated in Fig. 7(d). From the figure, relatively large stresses with different directions are shown in both the front and the rear sections of the capsule. This result indicates that the shear stress shown in the front section of the capsule acts as the resistance force against the capsule movement but, on the contrary, the stress in the rear section of the capsule acts as the propulsion force for helping the capsule advance.

Figure 8 presents a comparison between the change in the hoop stress with respect to time from the FE analysis and that given by the analytical prediction model proposed in section 2 when the capsule of 10 mm diameter and 20 mm length moves with a speed of 0.5 mm/s. This figure clearly shows that the change in the hoop stress values obtained from the FE analysis corresponds quite well to that of the proposed prediction model.

The fixed-end boundary conditions for the FE analysis are quite different from the actual situation of the intestine inside the body. The boundary conditions used in the FE analysis, however, were the same as the experimental conditions where both ends of the pigs intestine specimen were fixed in order to prevent it from rotating or moving in the sliding direction of the capsule. Such boundary conditions and uncertainties of the viscoelastic material properties of the small intestine can be the limitations of the FE model. The fact that the peristalsis movement of the small intestine in the living body was not considered is also a limitation of the FE model. Furthermore, the ‘straight tube with a constant diameter’ geometry of the FE model should be mentioned as another constraint. Compared with the random droop or curl of the intestine in front of the capsule both in the living body and the in-vitro experiment, such a definite model may give undesirable results. Nevertheless, the analyses performed in this work provided a fundamental insight into the stress interaction between the capsule and the intestine.

4 CONCLUSIONS

An analytical model for the frictional resistance prediction of a self-propelled capsule endoscope moving inside the small intestine was first developed. The model was developed by considering the intestine as a pressure vessel from the biomechanical viewpoint, based on the experimental investigations on the viscoelastic characteristics of the intestine and the frictional resistance of the capsule.

From the comparison of the frictional resistance between the predicted and the experimental values, it could be found that the predicted frictional forces were similar to the experimental results, even though some geometrical constraints on the deformation of the intestine resulted in relatively large differences in the case of the capsule of small size. Also, as a method to verify the validity and accuracy of the prediction model, an FE analysis using a two-dimensional axisymmetric structure model for the capsule and the intestine was performed. The results from the FE study on the distributions of various stress components suggested that a relatively high stress could be created in the region of the intestine wall that was in contact with the front of the capsule and
the stress decreased towards the rear of the capsule owing to the stress relaxation characteristics of the small intestine. Also, it was found that relatively large shear stresses with different directions were shown in the front and rear sections of the capsule, and the hoop stress distribution along the capsule were very similar for the result of the prediction model and for that of the FE analysis.

The results of this work are expected to contribute to the design of a self-propelled capsule-type endoscope with optimal frictional interaction with the intestine surface.

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REFERENCES


APPENDIX

Notation

- $D_i(x)$: inner diameter of the intestine at a position $x$ along its length (mm)
- $E$: elastic modulus of a spring component (Pa)
- $F$: frictional force of the capsule (N)
- $F_p$: frictional force induced by the stress due to the peristalsis movement of the intestine (N)
- $F_v$: frictional force induced by the stress due to the viscoelastic deformation of the intestine wall (N)
- $F_w$: frictional force related to the capsule weight (N)
- $g(x)$: geometrical shape function of the contact surface
- $p(x)$: resisting force per unit area generated by the pressure (N)
- $q(x)$: pressure (Pa)
- $S$: area of contact surface between a capsule and the small intestine (mm$^2$)
- $v$: moving speed of a capsule (mm/s)
- $\gamma(t)$: strain applied to the intestine at the time $t$
- $\eta$: viscosity of a dashpot component (Pa s)
- $\rho(x)$: wall thickness of the intestine at a position $x$ along its length (mm)
- $\mu$: friction coefficient
- $\sigma_\theta$: hoop stress (Pa)