Interaction model between capsule robot and intestine based on nonlinear viscoelasticity

Cheng Zhang¹,², Hao Liu¹, Renjia Tan¹,² and Hongyi Li¹

Abstract
Active capsule endoscope could also be called capsule robot, has been developed from laboratory research to clinical application. However, the system still has defects, such as poor controllability and failing to realize automatic checks. The imperfection of the interaction model between capsule robot and intestine is one of the dominating reasons causing the above problems. A model is hoped to be established for the control method of the capsule robot in this article. It is established based on nonlinear viscoelasticity. The interaction force of the model consists of environmental resistance, viscous resistance and Coulomb friction. The parameters of the model are identified by experimental investigation. Different methods are used in the experiment to obtain different values of the same parameter at different velocities. The model is proved to be valid by experimental verification. The achievement in this article is the attempted perfection of an interaction model. It is hoped that the model can optimize the control method of the capsule robot in the future.

Keywords
Interaction model, nonlinear viscoelasticity, intestine, capsule robot, dynamic mechanical analyzer

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Introduction
A robotic capsule endoscope that can move actively with the doctor’s operation has been not only the development direction of the capsule endoscopy but also a research hotspot in the field of robotics and medicine over recent decades. A magnetically guided capsule endoscope (MGCE) system had been developed by Siemens and Olympus, and more than 50 people conducted clinical practice at 2010.¹ It is another landmark achievement after the first passive capsule endoscopy developed by Given Imaging at 2001.² The MGCE system can only examine the stomach in clinic and need to be operated by the doctor in the entire checking process, although it solves some of the problems of the passive capsule endoscopy, such as time-consuming, misdiagnosis and ileus.³ The deficiency of the interaction model between capsule robot and intestine may be one of the dominating reasons that the MGCE system abandons the inspection in the gastrointestinal tract.

As the main environment of the capsule endoscopy, the intestine is a complex flexible lumen, the inwall of which is covered by mucus. Any drive mode⁴–¹³ cannot neglect the influence of this complex environment on the capsule robot’s motion when the capsule robot moves in the intestine. Currently, no mathematical model can describe the interaction force between the capsule robot and the intestine precisely. Many developers are engaged in the field of intestinal environment modeling. Hoeg et al. studied the tissue distention of the intestine under the condition of a robotic endoscope moving through. An analytical model and an experimental model were developed to predict the tissue behavior when the intestine was expanded.¹⁴ Huang and colleagues¹⁵ analyzed the interactive feature changes under the influence of various diameters, lengths and materials of the capsule robot by means of experimental investigation. Some similar researches were carried out by Wang and Meng,¹⁶ Wang and Yan¹⁷ and our group¹⁸ as well. Ciarletta et al.¹⁹ used the theory of hyperelasticity to make a stratified analysis of the

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intestinal wall. The hyperelastic model is inapplicable to research the intestinal material property because it neglects the time effect. Woo et al.\textsuperscript{20} considered the interactive feature using a thin-walled model and Stokes’ drag equation. However, the model cannot fully describe the material characteristics of the intestine. Most of these research works establish a qualitative empirical interaction model by experimental investigation. In addition, the features of the capsule robot also affect the interaction force. These features contain not only dimension parameters but also motion parameters. At present, the viscoelastic constitutive relation is supposed to be the most effective method of describing the material properties of the intestine. Baek et al.\textsuperscript{21} investigated the frictional resistance of a capsule inside the porcine small intestine with respect to various capsule shapes using a specially designed tribological tester. Then, the group found that variations of resistance were correlated with the linear viscoelastic property of the intestine. A five-element model is used to describe the linear viscoelastic property of the intestine’s stress relaxation.\textsuperscript{22} Furthermore, the group first developed an analytical model for the frictional resistance prediction that was verified by finite element analyses.\textsuperscript{23} In our study, we show that the parameters in the viscoelastic constitutive relation are not constant.\textsuperscript{24} In other words, the linear viscoelastic constitutive relation is insufficient to describe the intestinal material property. Most researchers used in vitro experiment instead of in vivo experiment in the study process because the latter costs more and is difficult to carry out. It is considered a more convenient choice to simulate the in vivo environment in the in vitro experiment.

In this article, an interaction model between the capsule robot and the intestine is developed to solve the problem that the capsule robot cannot complete the controlled movement in the intestine. The model has something to do with the motion parameters of the capsule and the nonlinear viscoelasticity of the intestine. The model parameters are identified by static mechanical test, such as shear stress relaxation test, and dynamic mechanical test with dynamic mechanical analyzer (DMA). At last, the validity of the model is verified by in vitro experiment. The achievement in this article is hoped to optimize the control method of the capsule robot.

**Interaction model between capsule robot and intestine**

The interaction model is affected by the properties of the capsule robot and intestinal material parameters. The intestine is expanded when the capsule moves inside because of the intestinal contraction in a relaxed state (see Figure 1). The shape of the capsule is a cylinder in the middle section and two hemispheres on both ends. The middle section is acted upon by a radial pressure and axial friction, while the pressure perpendicular to the contour line of the capsule is applied on the both ends of the capsule. When the capsule moves forward, the pressure on the rear end can be ignored. The interaction force along the \( x \)-direction is more important to the capsule robot’s movement, so it can be expressed as a resultant force of environmental resistance, viscous resistance and Coulomb friction\textsuperscript{25}

\[
F = F_e + F_v + F_c
\]

where \( F_e \) is the environmental resistance, \( F_v \) is the viscous resistance and \( F_c \) is the Coulomb friction.

Environmental resistance is induced by the stress due to the viscoelastic deformation of the intestinal wall. Viscous resistance is caused by the rheological properties of the intestinal mucus. Coulomb friction is a product of the local contact pressure and the Coulomb friction coefficient. Then, environmental resistance, viscous resistance and Coulomb friction will be analyzed.

**Intestinal deformation and environmental resistance analyses**

**Principle of environmental resistance and assumptions.** The deformation of the intestinal wall is the major influencing factor of the environmental resistance. As the front of the capsule is a hemisphere, the intestinal wall applies a contact force on its contact surface. The horizontal component of the contact force is defined as \( F_x \). For further development of the model, the following assumptions should be made.

1. The material of the intestine is incompressible.
2. The intestine consists of an isotropic material and deforms symmetrically toward its radial direction.
3. The deformation of the intestine is the same as the external shape of the contact surface of the capsule.

Based on the assumptions above, the deformation could be derived using the contact geometry between the intestine and the capsule.
Formula derivation of intestinal deformation and environmental resistance. The contact force is mainly caused by the hoop stress of the intestine. The relationship between the pressure $P(x)$ and the hoop stress $\tau_\theta(x)$ can be expressed as

$$\tau_\theta(x) = \frac{P(x)D_i(x)}{2\lambda_m}$$

(2)

where $D_i(x)$ and $\lambda_m$ are the inner diameter and the average wall thickness of the intestine at position $x$ along the length of the intestine, respectively. A five-element model had been used to describe porcine intestinal constitutive relation. It consists of three springs and two dampers (see Figure 2). An equation that shows the relation between stress and strain with respect to time is obtained from the results of a stress relaxation test

$$\tau_\theta(t) = \varepsilon(t) \left[ E_1 e \left( -\frac{\xi_1}{\eta_1} \right) + E_2 e \left( -\frac{\xi_2}{\eta_2} \right) + E_3 \right]$$

(3)

where $E_1$, $E_2$ and $E_3$ indicate the moduli of elasticity of springs, while $\eta_1$ and $\eta_2$ are the viscosity coefficients of the dampers. $\varepsilon(t)$ and $\tau_\theta(t)$ are the strain and stress applied to the intestine, respectively, at the time $t$. When the capsule moves at a constant speed $v$, equation (3) can be written as a function of the position $x$

$$\tau_\theta(x) = \varepsilon(x) \left[ E_1 e \left( -\frac{\xi_1}{\eta_1} \right) + E_2 e \left( -\frac{\xi_2}{\eta_2} \right) + E_3 \right]$$

(4)

The initial mean diameter of the intestinal inwall approximately equals

$$D_0 = 2R \cos \alpha$$

(5)

where $R$ is the radius of the hemisphere and $\alpha$ is the initial angle corresponding with the contact surface. The hoop strain with respect to position is defined as

$$\varepsilon(x) = \frac{D_i(x) - D_0}{D_0}$$

(6)

Therefore, the contact pressure is

$$P(x) = \frac{\varepsilon(x) \left[ E_1 e \left( -\frac{\xi_1}{\eta_1} \right) + E_2 e \left( -\frac{\xi_2}{\eta_2} \right) + E_3 \right] 2\lambda_m}{D_i(x)}$$

(7)

Then, the environmental resistance induced by the stress is

$$F_e = \int_0^{R \sin \alpha} 2\pi RP(x)dx \times \sin \theta$$

(8)

where $\theta$ is the angle of the equivalent contact force. The environmental resistance $F_e$ varies not only with the intestinal constitutive parameters but also with the velocity of the capsule according to equation (8).

Viscous resistance analyses

There is lot of mucus in the intestine because of its own physiological structure. The capsule robot is in complete lubrication condition in the whole moving process approximately. Viscous resistance is related to the relative velocity. It can be calculated from the empirical equation

$$F_\nu = \delta \nu$$

(9)

where $\delta$ is the apparent viscosity coefficient.

The intestinal mucus is a kind of non-Newtonian fluid. Its apparent viscosity decreases with increase in shear rate. When the shear rate is high enough, the apparent viscosity of the intestinal mucus becomes a constant. The apparent viscosity coefficient can be expressed as

$$\delta = 11.24 \left( \frac{V}{d} \right)^{-0.7552} + 0.1148$$

(10)

where $d$ is the mean value of the intestinal mucus thickness. The intestinal environment is complex. Different parts of the intestine have different morphology, such as mucus thickness and length of intestinal villi. The intestinal mucus thickness also varies depending on the force on the intestinal surface. An approximate value of $d$ will be used in the model.

Coulomb friction analyses

Coulomb friction is decided by the local contact pressure and the Coulomb friction coefficient

$$F_c = \mu N$$

(11)

where $\mu$ is the Coulomb friction coefficient and $N$ is the local contact pressure. The Coulomb friction coefficient is influenced by the surface texture of the intestine, especially the intestinal villi. The value of $\mu$ can be
calculated from the experimental results. The local contact pressure consists of the normal force and the radial pressure. The normal force is decided by the weight of the capsule, while the radial pressure is caused by the hoop stress of the intestine. The radial pressure is the vertical component of the skew resistance on the hemisphere of the capsule. The local contact pressure is expressed as

\[
N = mg + \int_{R \sin \alpha}^{R \sin \alpha + L} 2\pi RP(x)dx \times \cos \theta \\
+ \int_{R \sin \alpha}^{R \sin \alpha + L} 2\pi RP(x)dx \tag{12}
\]

where \(m\) is the mass of the capsule and \(L\) is the length of the capsule's middle section.

**Model parameter identification**

Several parameters should be confirmed to complete the model. Some parameters are predetermined, others need to be determined by experience and some must be measured by experiment.

The material, mass and dimension of the capsule are predetermined. The material is polydimethylsiloxane (PDMS). The mass \(m\) is 50.1 g. The length of middle section, that is, a cylinder, \(L\) is 20 mm, while the radius of the end, that is, a hemisphere, \(R\) is 6.5 mm. Based on practical experience, the initial angle corresponding with the contact surface \(\alpha\) is 60°, the angle of the equivalent contact force \(\theta\) is 30°, the average intestinal wall thickness \(\lambda_m\) is 2.5 mm and the mean value of the intestinal mucus thickness \(d\) is 30 \(\mu\)m. The Coulomb friction coefficient and the parameters of the five-element model need to be measured by experiment.

**Experiment of measuring Coulomb friction coefficient**

A custom-made physical simulation measurement system is used to measure the Coulomb friction coefficient. It consists of two parts: drive unit and data acquisition (DAQ) unit (see Figure 3).

The main part of the drive unit is a NLA-7SL series coreless linear motor, which is produced by NIKKI DENSO. The encoder is RGH22X-lum resolution, which is produced by RENISHAW. The positioning accuracy of the system can reach \(\pm 1 \mu\)m. The rotor of the linear motor is combined with a support, on which a single-degree-of-freedom micro-force sensor is fixed, whose accuracy is 1 mN. The right side of the drive unit is load platform. PCI 6229 DAQ card produced by NI is used to acquire the voltage signal of encoder and micro-force sensor. Then, the signal is transmitted to computer for saving and analysis. The negative pressure suction device is used to clamp the intestine and make it expand to 13 mm (see Figure 4). After both ends of the intestine are fixed, the air in vacuum bin is extracted from bleeder hole with a syringe. Then, the intestinal wall is absorbed by the device and expanded compulsively. The device is fixed on the load platform, and a capsule dummy is inserted into the intestine that is fully expanded.

Fresh intestine of a pig is used in the experiment. The intestine sample is stored and cleaned in Tyrode with oxygen ventilation. A length of intestine is placed in the negative pressure suction device. Then, the Coulomb friction is only caused by the weight of the capsule. The capsule whose dimension parameters are the same as that stated in the model is dragged by the drive unit at a speed of 0.5 mm/s. The mean value of Coulomb friction that is measured by the micro-force sensor is \(F_c = 40.07\) mN. The Coulomb friction coefficient is \(\mu = 0.082\) by calculation. This result agrees with the conclusion of Rentschler and colleagues.

**Experiment of measuring the parameters of the five-element model**

A shear stress relaxation test is used to measure the parameters of the five-element model also with the homemade physical simulation measurement system.
The capsule dummy is changed to a cylinder, whose diameter is 12.9 mm and length is 15.2 mm, and there are asperities on its surface. These asperities will ensure that there is no relative slippage between the dummy and the intestine. The experimental shear strains, which are the ratios of the intestinal elongation and the intestinal wall thickness, are 50%, 100%, 150% and 200%. The shear stress curves with different strains are obtained by means of curve fitting, and then, the parameters of the five-element model are confirmed (see Table 1).

The moduli of elasticity and the viscosity coefficients of the five-element model are not constant, but vary with shear strains according to the data in Table 1. Therefore, the relations between the parameters of the five-element model and the shear strains are

\[
\begin{align*}
E_1 &= -0.1617\varepsilon^2 - 0.3175\varepsilon + 3.348 \\
E_2 &= 0.1729\varepsilon^2 - 1.078\varepsilon + 2.078 \\
E_3 &= 0.1653\varepsilon^2 - 0.9792\varepsilon + 1.877 \\
\eta_1 &= -0.01386\varepsilon^2 + 0.03667\varepsilon + 0.0442 \\
\eta_2 &= 0.0185\varepsilon^2 - 0.2205\varepsilon + 0.6971
\end{align*}
\]

Substituting the above parameters to the model, a curve that describes the relation between the interaction force and the velocity of the capsule is obtained. Figure 5 shows the comparison between the experimental results that had been obtained in our previous work and the model-predicted results. Different contributions are made by three components of the force in the model. Environmental resistance is affected by the velocity greatly and occupies a major share in the frictional resistance. Viscous friction is also affected by the velocity, but in a small proportion. Coulomb friction has little relationship with the velocity. Therefore, the influence of the inaccuracy of the mucus thickness can be ignored easily.

It is shown that the effect of the model prediction is great at the velocity lower than 20 mm/s, but that at a speed range from 20 to 60 mm/s is not satisfactory in Figure 5. We deduce that the parameters of the five-element model may be changed at a relatively higher velocity. Therefore, a new experimental method is proposed to accomplish the parameter identification.

### Parameter identification of the five-element model at a relatively higher velocity

The classic shear stress relaxation test is not efficient to obtain the parameters of the model when the capsule robot moves at a relatively higher velocity. In other words, the viscoelasticity of intestinal material should be analyzed at a certain frequency. It is called dynamic viscoelasticity.

#### Dynamic viscoelasticity of intestinal material

The constitutive equation of the five-element model needs to be derived according to the model structure and the properties of the springs and dampers

\[
\begin{align*}
\sigma &= \sigma_1 + \sigma_2 + \sigma_3 \\
\dot{\varepsilon}_1 &= \dot{\sigma}_1/E_1 + \sigma_1/\eta_1 \\
\dot{\varepsilon}_2 &= \dot{\sigma}_2/E_2 + \sigma_2/\eta_2 \\
\sigma_3 &= E_3 \cdot \varepsilon_3 \\
\varepsilon &= \varepsilon_1 = \varepsilon_2 = \varepsilon_3
\end{align*}
\]

where \(\sigma_1, \sigma_2\) and \(\sigma_3\) are the stresses of the three parallel branches of the model, while \(\varepsilon_1, \varepsilon_2\) and \(\varepsilon_3\) are the strains, respectively.

Solving equation (14), we get

\[
\dot{p}_0\sigma + p_1\dot{\sigma} + p_2\ddot{\sigma} = q_0\varepsilon + q_1\dot{\varepsilon} + q_2\ddot{\varepsilon}
\]

where \(\sigma\) and \(\varepsilon\) are the stress and strain of the model, respectively.

![Figure 5. Comparative data of the relation between the interaction force and the velocity.](image-url)
Table 2. Experimental results of the shear test on DMA apparatus.

<table>
<thead>
<tr>
<th>$\omega$ (Hz)</th>
<th>Sample 1</th>
<th></th>
<th>Sample 2</th>
<th></th>
<th>Sample 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$Y_1$ (MPa)</td>
<td>$Y_2$ (MPa)</td>
<td></td>
<td>$Y_1$ (MPa)</td>
<td>$Y_2$ (MPa)</td>
</tr>
<tr>
<td>20</td>
<td>0.5494</td>
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<td></td>
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</tr>
<tr>
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<td>0.4507</td>
<td></td>
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<td>0.4456</td>
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<tr>
<td>40</td>
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<td>0.5011</td>
<td></td>
<td>0.5042</td>
<td>0.5046</td>
</tr>
<tr>
<td>50</td>
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<td>0.6466</td>
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<td>0.8144</td>
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</tr>
<tr>
<td>60</td>
<td>0.6749</td>
<td>0.4706</td>
<td></td>
<td>0.6942</td>
<td>0.4910</td>
</tr>
</tbody>
</table>

Let

$$Y^*(i\omega) = Y_1(\omega) + iY_2(\omega)$$

$$= \frac{Q(i\omega)}{P(i\omega)}$$

$$= \frac{q_0 + q_1(i\omega) - q_2\omega^2}{p_0 + p_1(i\omega) - p_2\omega^2}$$

where $Y_1(\omega)$ is the storage modulus and $Y_2(\omega)$ is the loss modulus. Solving the equation yields

$$Y_1(\omega) = \frac{[E_1E_2E_3 - (E_1 + E_2 + E_3)\eta_1\eta_2\omega^2](E_1E_2 - \eta_1\eta_2\omega^2)}{(E_1E_2 - \eta_1\eta_2\omega^2)^2 + (E_2\eta_1 + E_1\eta_2)^2\omega^2}$$

$$Y_2(\omega) = \frac{[(E_1 + E_3)E_2\eta_1 + (E_2 + E_3)E_1\eta_2][E_1E_2 - \eta_1\eta_2\omega^2] - (E_2\eta_1 + E_1\eta_2)^2\omega^2}{(E_1E_2 - \eta_1\eta_2\omega^2)^2 + (E_2\eta_1 + E_1\eta_2)^2\omega^2}$$

**Shear test with DMA and data processing.** Dynamic mechanical analysis (DMA), is a technique where a small deformation is applied to a sample in a cyclic manner. This allows the materials' response to stress, temperature, frequency and other values to be studied. This technique is appropriate to measure the relationship between the strain and the stress at a certain frequency. The equipment type used in this article is TA Instrument DMA Q800.

Fresh intestine of a pig is used in the experiment. The intestine sample is stored in Tyrode with oxygen ventilation. A length of jejunum is chosen as the experimental subject. The jejunum is cut to small square samples whose average length of the side is 5.5 mm. The samples are placed in the shear test fixture and clamped in the direction of the arrows shown in Figure 6. After that the drive unit is controlled to move up and down. The experimental temperature is maintained at 37 °C. The experiment proceeds with a constant strain 4%
and a varying frequency from 20 to 60 Hz. The experimental results of three samples are shown in Table 2. It is acceptable that the maximal deviation in Table 2 is 7.92%. Substituting the average value of the experimental results into the expression of the storage modulus and loss modulus yields the parameter values of the five-element model. These parameter values are shown in Table 3.

Comparing with the parameter values of the five-element model obtained from the classic shear stress relaxation test, $E_1$ and $\eta_1$ in Table 3 decrease to a great extent. That is to say, when the frequency is higher than 20 Hz, the five-element model can be simplified to a parallel connection with both a Maxwell model and a spring.

It is generally known that the frequency of applied stress or strain has great influence on the mechanical properties of materials, and the intestinal material has no exception. When the frequency is 20 Hz, the velocity of the shearing motion is 17.6 mm/s, which is calculated according to the size of the sample and the shearing strain. That is to say, the velocity of the shearing motion is higher than 17.6 mm/s when the frequency is greater than 20 Hz. Therefore, it is reasonable that the parameters of the five-element model at a speed range from 20 to 60 mm/s can be obtained from the shear test with DMA.

The model-predicted result of the updated interaction model is shown in Figure 7. The data of interaction force ranging from 0 to 20 mm/s are obtained from the model with the parameters obtained by the shear stress relaxation test, while the data ranging from 20 to 60 mm/s are obtained from the updated mode. There is an obvious inflection point at the velocity of approximately 20 mm/s because of the change of the parameters of the five-element model.

Model validation and discussion

The validity of the model-predicted results will be verified by an experiment. A homemade mechanical test platform is used in the experiment (see Figure 8). A stepper motor (86BYG350CH; SYNTRON) with its driver (SH32206; SYNTRON) is chosen to drive a guide screw (THK KR55). A micro-force sensor (FUTEK LSB200) is fixed on the slider of the guide screw. The probe of the force sensor is connected to a capsule that is placed inside the intestine with a polymer string. A length of jejunum is also chosen as the experimental subject, which is preconditioned with the same method as in the shear test with DMA. Flexible polyurethane foam (PUF) is used as the basement that is fixed on the load platform. The mesentery and one side of the intestine specimen are fixed on the basement. DAQ system (NI DAQ PCI6229) is used to acquire the voltage signal of the force sensor. Then, the signal is transmitted to the computer for saving and analysis.

The capsule moves at a constant velocity in the intestine. The relationship between the velocity and the friction can be obtained with the test platform. Different parts of the intestine have different diameters, wall thicknesses, lengths of intestinal villi and so on. Different parts of the intestine also have different mechanical properties. Therefore, two samples of jejunum are used to overcome the biodiversity and improve the reliability of the experimental results. The experimental results are shown in Figure 9. The variation trends of the two experimental results are similar. It is shown that the results of the verification test are repeatable and reasonable. In addition, the experimental results are similar to those in Zhang et al. Figure 9 also shows the comparison between the experimental results and the theoretical results. Next, the goodness
of fit will be estimated by $R^2$ at the velocity larger than 20 mm/s.

$R^2$ is the square of the correlation between two sets of data. It is also used to measure how successful the fit is in explaining the variation of the data. The formula of $R^2$ is

$$R^2 = \frac{\sum_{i=1}^{n} (\tilde{F}(i) - \bar{F})^2}{\sum_{i=1}^{n} (F(i) - \bar{F})^2}$$  \hspace{1cm} (20)$$

where $\tilde{F}$ is the theoretical results and $F$ is the experimental results. The $R^2$ between the theoretical results and the experimental results of sample 1 is 0.9928, while that of sample 2 is 0.9901. The analysis shows that the interaction model can describe the interaction force between the capsule and the intestine efficiently, and it is closely related to the intestinal constitutive relation and the capsule’s velocity. The parameters of the five-element model are not constant. The classic linear viscoelastic model is not sufficient to describe the material properties of the intestine. Moreover, these parameters are proved to have something to do with the velocity of the intestinal deformation, which relates to the velocity of the capsule.

The intestine is a complex physiological environment, which contains three parts: duodenum, jejunum and ileum. Every part of the intestine has different mechanical characteristics, and the intestine itself has biodiversity. The intestine has the ability to move autonomically, which manifests as periodic hastral segmentation, peristalsis and tonic contraction. This autonomic movement cannot be neglected in intestinal environment modeling. In this article, a length of jejunum is used in the experiment and the intestinal peristalsis is neglected. The interaction model that is applicable to other parts of the intestine will be developed too. More experiments will be done to obtain more accurate and systematic parameters. The wave of intestinal peristalsis is being researched intensively. It will make the interaction model more general. These ideas will also be our future work.

Both our work and the research of Kim et al.\textsuperscript{22} have proved that the five-element model is suitable to describe the viscoelastic property of the intestine. Meanwhile, we find that the parameters of the five-element model change when the capsule moves in the intestine at different velocities. This change happens at a speed of approximately 20 mm/s. We speculate that the viscoelastic constitutive equation of the intestine alters when the velocity changes. Some research shows that intestinal mucous layer and muscularis have different material properties. The mucous layer has obviously viscoelastic characteristics, while the muscularis manifests as hyperelasticity.\textsuperscript{19} The intestine radially deforms with mucous layer’s significant viscoelastic effect when the capsule moves slowly, whereas the hyperelasticity of the muscularis plays a leading role. Therefore, intestinal constitutive model will change with the deformation rate, which is consistent with the experimental results in this article. Whether the velocity boundary between the lower velocity area and the higher velocity area is an accurate value needs to be studied continuously.

Currently, most of the capsule robots move at a lower velocity in the intestine, such as bionic movement, spiral movement and legged movement. However, a vibro-impact capsbot with the “internal force–static friction” driving principle, which is first developed by our group, has an instantaneous speed that can reach up to 60 mm/s. A sliding mass reciprocates in the shell of the capsbot with different accelerations, and then, the capsbot can move forward or backward.\textsuperscript{32} The capsbot can move on a hard surface at an average velocity of 10 mm/s. But the efficiency decreases when the capsbot moves in the intestine. The main reason for the decrease in efficiency is that the control strategy used on the hard surface is used in the intestine directly. The imperfection of the interaction model between the capsule robot and the intestine makes the control strategy difficult to be optimized,
especially at a higher velocity. The achievement in this article is hoped to be useful to optimize the control strategy of the capsubot. More work needs to be done to make the capsubot to move in the intestine efficiently.

Conclusion

An interaction model is established to describe the interaction force between the intestine and the capsule robot based on the nonlinear viscoelasticity of the intestinal material in this article. The nonlinear viscoelastic model is used to analyze the material properties of the intestine, and its parameters have something to do with the velocity of the intestinal deformation, which relates to the velocity of the capsule. Different experimental methods are used to measure the parameters of the model at different velocities of the capsule robot. The model is proved to be reasonable to describe the interaction force. The achievement in this article is hoped to perfect the interaction model and optimize the control method of the capsule robot, especially the vibro-impact capsubot.

Declaration of conflicting interests

The authors declare that there is no conflict of interest.

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