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Modeling and experimental investigation of rotational resistance of a spiral-type robotic capsule inside a real intestine

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Abstract

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Keywords

rotational, resistance, spiral, modeling, type, experimental, robotic, capsule, inside, real, intestine, investigation

Disciplines

Engineering | Science and Technology Studies

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Modeling and Experimental Investigation of Rotational Resistance of a Spiral-Type Robotic Capsule Inside a Real Intestine

Hao Zhou, Gursel Alici, Trung Duc Than, and Weihua Li

***Abstract*—In this study, the rotational resistance of a spiral-type capsule rotating inside a small intestine is investigated by *in vitro* experiments and analytical modeling, on which a limited literature is available. The results presented exhibit viscoelastic nature of the intestinal tissue. The significance of various spiral structures and rotating speeds is quantitatively evaluated from the propulsion point of view. Also, an analytical torque model is proposed and subsequently validated. The close match between the experimental results and numerical results from the model shows that the model is reasonably accurate to estimate the rotational resistance torque of the small intestine. Both the experimental and modeling works provide a useful guide to determine the torque required for a spiral-type endoscopic capsule operating in a "really" small intestine. Therefore, the proposed torque model can be used in the design and optimization of in-body robotic systems, which can remotely be articulated using magnetic actuation.**

***Index Terms*—.**

I. Introduction

THE wireless capsule endoscope (WCE) has been universally used as a first-line medical tool to diagnose diseases in the gastrointestinal (GI) tract, especially in the small intestine, where traditional endoscopes are hard to access [1]–[3]. It is believed that more attractive applications of WCE, such as targeted drug delivery and telepresence surgery, will be realized in the near future if a robotic capsule with active locomotion is developed to break its dependence on the natural peristalsis for movement [4].

Significant effort has been dedicated to exploring novel locomotion mechanisms [5]–[8]. Among them, magnetic propulsion is promising since it does not require onboard batteries and the control unit is moved out of the capsule, too. Therefore, much space can be saved, which is a vital advantage for a millisized robotic device or even smaller size. In addition, a limited operation time will no longer be a problem due to remotely powering of a magnetically propelled robotic device.

Two approaches are generally adopted to implement magnetic propulsion. The first approach [9]–[11] is straightforward, exerting a direct pulling force on an internal magnetic part by producing a magnetic field gradient. However, this pulling force decays rapidly when the gap between the robot and the magnetic source increases. The second approach [12], [13] is based on embedding a magnet with its magnetization lateral to the capsule's axis and then generating a rotating magnetic field so that the capsule can be acted upon by a magnetic torque and hence the capsule spins about its axis. When a spiral structure is mounted on the capsule's surface, the rotation is converted to a translational movement. Compared to the direct-pulling method, the propulsion of a spiral-type robot is advantageous because the maximum torque available to the robot is proportional to the magnetic field intensity, which declines slower than the magnetic field gradient over a long distance. Three-axis Helmholtz coils with three separate sinusoidal current inputs are able to produce a rotating magnetic field with a uniform intensity and an adjustable rotational axis so that the robot is propelled and steered along the curved GI tract [13].

To develop a spiral-type WCE, the geometry of the helical structure must be optimized since it plays a significant role in determining the propulsion efficiency. As a medical microrobot traveling in a deflated, winding, and slippery lumen, the complexity of its working environment makes this optimization problem even more critical. Therefore, the resistant characteristics of the GI tract should be evaluated in order to provide more accurate data with the optimization process.

Recently, some research work has been reported on the biomechanical and tribological properties of the GI tract. Baek *et al.* measured the frictional resistance of capsules with different shapes and dimensions moving along porcine small intestinal samples and concluded that a smooth cylindrical capsule with a smaller diameter performed better in avoiding translational friction [14]. In their work, they investigated the small intestine's properties further and reported on a viscoelasticity model for the stress relaxation [15] as well as an analytical model [16] to predict the friction from a linear movement of a smooth cylindrical capsule inside the small intestine. Wang and Meng conducted a series of tests with 15 plastic capsules of various diameters and lengths inside the segments of porcine small intestine [17]. The resistant forces from 20 to 100 mN were measured for the capsules which had the diameters in the range of 8–13 mm and the translational speed of 0.5 mm/s. Wang and Yan performed

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the tests by pulling a set of specially prepared frictional samples with different surface profiles on planar open intestinal samples [18]. The tests showed that a flat contact surface caused the least resistance while a triangular one led to the most. Terry *et al.* performed experiments on active forces from the myenteron, biomechanical response, mucus adhesivity, and tribology of the porcine small intestine [19]. By comparing the *in vivo* and *in vitro* tribometry tests, it was suggested that the coefficient of friction (COF) might slightly drop as the tissue became dead. Bellini *et al.* proposed a constitutive model, with parameters identified from planar biaxial test data, to predict biomechanical response of the small bowel under complex loading [20]. All these work has contributed to a better understanding of the mechanical properties of the small intestine for active capsule endoscopes. However, none of them studied the frictional resistance for a spiral-type capsule rotating inside a small intestine, which represents the real operation condition of a robotic capsule. This study aims to close this gap in the literature by establishing a mathematical model to predict the mechanical torque required to rotate the robotic capsule in a viscoelastic environment such as the GI tract.

This paper investigates the rotational resistance of a spiral-type capsule rotating inside the GI tract. From a physiological point of view, this is the resistance which the robotic capsule must overcome in order to start and maintain its rotation. The small intestine of a porcine was employed for the *in vitro* experiments since its mechanical properties were reported to be quite similar to those of a human being [21]. Four capsules with different spiral structures were tested under various rotating speeds. The rotational resistance was measured and presented in the form of torque. Furthermore, an analytical model was proposed for the prediction of this frictional resistance. Some parameters were identified with one set of experimental results and other sets of experimental results were used to further validate the model. This study provides a useful guide to characterize the required torque for a spiral-type capsule and to undertake the design and optimization of the microrobots' traction topology.

II. Experiments

A. Experimental Setup

Dummy Pillcam SB2 capsules (Given Imaging) were adopted as the bases of the microrobots. For each capsule, a segment of wire (ϕ 1 mm) was wounded around the outer surface and acted as the spiral structure. The winding area was within the cylindrical part of the capsule so that every spiral structure had the same dimension (15 mm) in the longitudinal axis. Four spiral-type capsules of such were fabricated, with the helical angles of 5° (No. 1), 10° (No. 2), 15° (No. 3), and 20° (No. 4), respectively, as shown in Fig. 1. For each of them, only one spiral was attached on the surface.

A steel rod was fixed to one end of the capsule so that the assembly could be connected to a torque sensor, which was able to output real-time measurements to its indicator. Via an RS232 cable and an interface program, the data were consequently sent to a PC for recording. During the tests, the capsule was kept still and the small intestine was spinning instead. The segment was

Fig. 1. Capsules with different spiral structures.

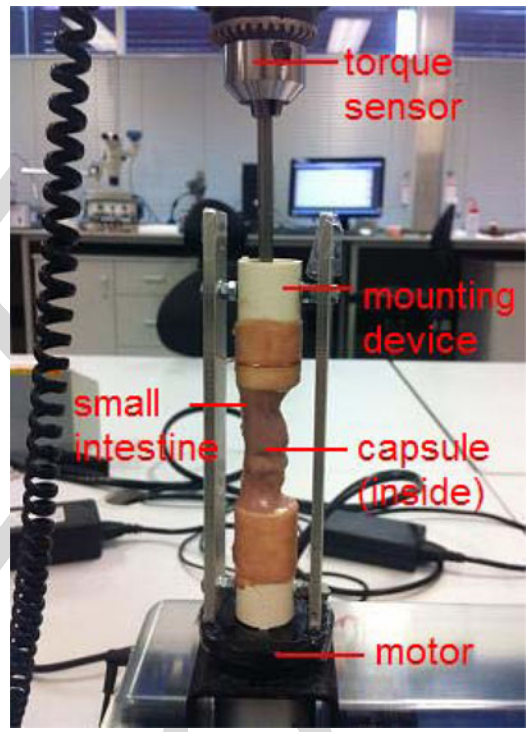

Fig. 2. General view of the experimental setup.

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mounted on a custom-built device, comprised of two coaxial plastic tubes and two aluminum bars for supporting. Then, this device was attached to an electric motor, whose rotating speed was adjusted by a Labview program sending commands via a data-acquisition (DAQ) board and a control module. In order to avoid the influence from the gravity, the devices were lined up vertically. The general view of the experimental setup is illustrated in Fig. 2.

B. Experimental Procedures

The intestinal specimens, kept in a refrigerator, were unfrozen a few hours before the experiments. Then, they were immersed in a jar of physiological saline, which was helpful to prevent tissue rupture. One intestinal segment and one capsule were placed as shown in Fig. 2 each time. The small intestine was rotated at a constant speed for several seconds by the electric motor so that the real-time frictional torque could be measured by the torque sensor. An initial test was carried out with one specimen

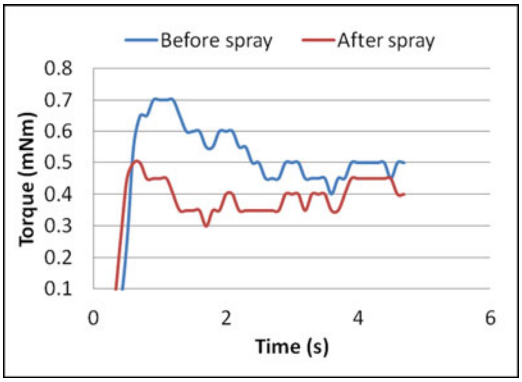

Fig. 3. Initial test with the small intestine Sample 1.

(Sample 1). Afterward, a set of tests were performed with the other two intestinal specimens successively. The internal diameters were 10.9 mm (Sample 2) and 11.1 mm (Sample 3), respectively. Both of them had the thickness of 1 mm. For each set of test, the rotating frequencies in the range of 0.5–3 Hz were applied.

The small intestine would be dried out fast once it was displaced out of the fluid. However, the saline could not be sprayed on the segment during the experiment since it would change the frictional properties of the intestine, as explained in the following section. Therefore, in order to keep the experimental conditions as consistent as possible, the tests were finished in a short time for either Sample 2 or Sample 3. Additionally, after each measurement, the sample was inspected whether a slight twist occurred due to the contact with the capsule. If so, a quick and simple treatment would be conducted manually to bring it back to the original state.

When all the tests for one specimen were finished, the intestinal tube was cut open and flattened on a table immediately. By using a force sensor and a smooth capsule with the mass of 3.98 g, the COF was determined for each intestinal specimen by the following equation:

$$\mu = \frac{f}{mg} \tag{1}$$

where f is the force to overcome the friction, and m is the mass of the pulled capsule, and g is the gravity of earth.

All the experiments were carried out in an air-conditioned space, which maintained the room temperature at 25 °C.

C. Results and Discussions

Fig. 3 shows the torque measurements with the capsule No. 2 (helical angle = 10°) and the small intestine Sample 1 under the rotating frequency of 1 Hz. Fig. 4 shows the results with two different segments. From Fig. 4, a slightly higher static friction occurs first and then a relatively steady dynamic friction can be observed. After spraying some saline on Sample 1, a reduction in the frictional resistance is quite apparent, implying the change of the tissue's biomechanical and tribological properties due to the absorption of liquid. Therefore, humidifying the intestine during

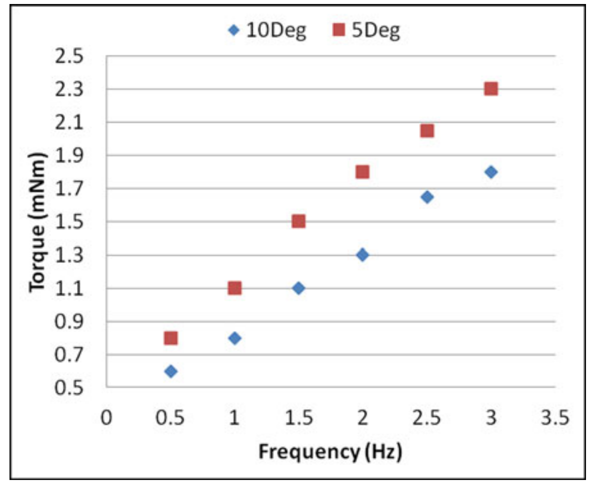

Fig. 4. Torque Measurement with the small intestine Sample 2.

the tests is inappropriate for the consistence of the experimental environment.

In the tests with Sample 2 and Sample 3, the measurements of dynamic friction are compared to each other as different combinations of capsule and intestinal specimens as well as frequency were adopted.

Sample 2 was tested with the capsules No. 1 (helical angle = 5°) and No. 2, respectively. The results are shown in Fig. 4. From the graph, it is seen that the frictional torque increases as the rotation frequency rises, indicating the rotational resistance has a relationship with the rate of strain of the small intestine. This dependence reveals the viscoelasticity of the GI tract to some extent. Due to the introduction of the spiral, the cross section of the capsule in the lateral direction is raised, increasing the deformation of the intestine. This increase becomes larger when the helical angle gets smaller. Therefore, when the number of spiral is the same, a capsule with a smaller helical angle causes more strain in the intestine, and consequently, confronts a higher frictional resistance. In this case, from 0.5 to 3 Hz, the capsule No. 2 (helical angle = 10°) causes a torque in the range of 0.6–1.8 mN·m while the capsule No. 1 (helical angle = 5°) results in the magnitude between 0.8 and 2.3 mN·m. At low frequencies, the torque is almost proportional to the frequency and the proportionality constant is bigger when the helical angle is smaller.

Sample 3 was tested with all the four capsules one by one. The torque measurements are presented in Fig. 5. For the same combinations of capsule, specimen, and frequency, the results are slightly different from those of Sample 2 due to the discrepancy of two intestinal specimens' conditions. However, the magnitude of the resistant feature is still in the same order. Moreover, the trend is nearly identical to that of Sample 2.

The COFs of two intestinal segments were also determined by (1) for the parameter identification of the analytical model proposed in the following section. Fig. 6 shows a sample measurement of the force versus time for the smooth capsule to overcome the friction on the cut-open and flattened small intestine (Sample 2). Since the mass of the capsule is already known,

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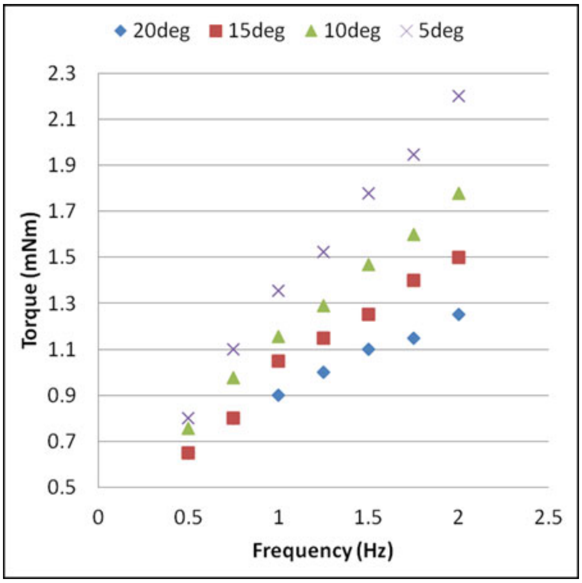

Fig. 5. Torque Measurement with the small intestine Sample 3.

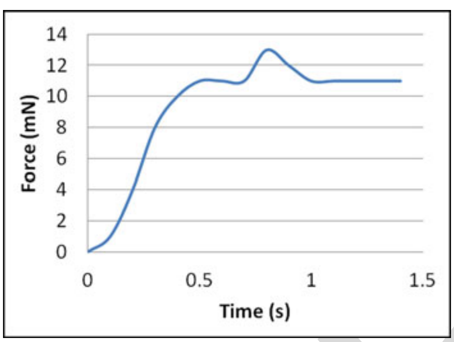

Fig. 6. Force history for a smooth capsule to overcome the friction on the cut-open and flattened small intestine Sample 2.

the COF for Sample 2 can be calculated as 0.28. The same method is used to find the COF for Sample 3, which is equal to 0.51. We postulate that the difference between these COFs can be due to different wetness conditions on the inner surfaces of these two samples. The inner surface of Sample 2 was slightly humidified with the saline before it was tested while the same treatment was not applied to Sample 3. As reported before, a small amount of lubrication could change the friction in a small intestine dramatically [17].

III. Modeling

A. Viscoelasticity Model

Generally, the relationship between stress and strain of a viscoelastic material can be illustrated by a generalized Maxwell model including multiple viscous dashpots and elastic springs [22]. Fig. 7 shows a five-element linear viscoelastic model, which is employed to describe the mechanical behavior of the small intestine in this study. The constitutive equation is expressed as follows:

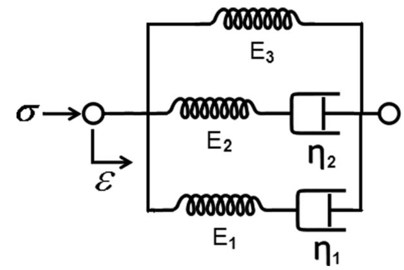

Fig. 7. Five-element viscoelasticity model.

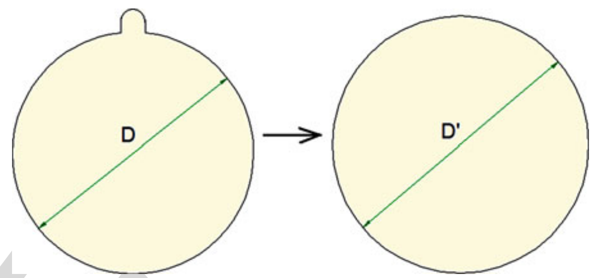

Fig. 8. Conversion of the inner intestinal wall's profile.

$$\sigma(t) = \varepsilon(t)\left[E_1 \exp\left(-\frac{tE_1}{\eta_1}\right) + E_2 \exp\left(-\frac{tE_2}{\eta_2}\right) + E_3\right] \quad (2)$$

where σ and ε denote the stress and the strain at the time t, respectively, and E_1, E_2, and E_3 are the elastic modulus of springs, and η_1 and η_2 represent the viscosities of dashpots.

B. Analytical Model for Rotational Resistance

As discussed earlier, attaching a spiral structure on the surface increases the cross section of the capsule in its lateral direction. In Fig. 8, the left-hand side profile describes the inner wall's cross-sectional profile of the small intestine after its deformation due to the insertion of the spiral-type capsule. The bulge results from the spiral structure and the parameter D indicates the diameter of the cylindrical part of Pillcam SB2 capsule (11 mm). To simplify the analysis, as the capsule rotates, the contour is converted to a circular geometry whose perimeter is comparable to the total length of the original one, which means the circumferential extension of the intestinal tract is kept the same. The right-hand side profile in Fig. 8 shows the converted circular profile of the deformed intestine's inner surface with a new diameter of D'. Since the spiral is only wounded on the cylindrical part, D' is just applied to calculate the strain of tissue for this area. The practical dimensions are used for the frontal and rear parts.

In addition to this geometrical simplification, a few assumptions are made to develop the model.

1) The intestinal tissue is an isotropic and incompressible material.
2) The volume and the wall thickness of the small intestine are constant.

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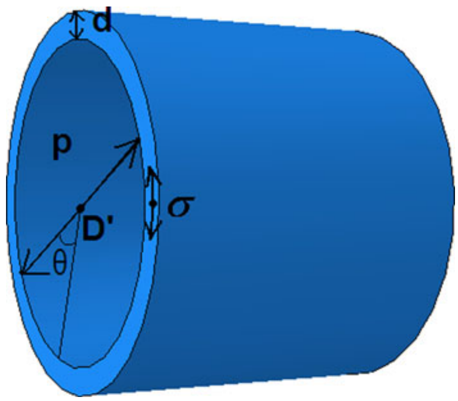

Fig. 9. Pressure vessel for the intestinal tract modeling.

3) The deformation of the intestine corresponds to the contact area and is symmetrical toward the radial direction after the geometrical simplification.

In order to analyze the normal load exerted on the capsule, the internal pressure generated by the intestinal tract due to circumferential extension has to be determined. Therefore, the intestine is modeled as a cylindrical pressure vessel [23] shown in Fig. 9. The pressure can be calculated from

$$p(\theta) = \frac{\sigma(\theta)2d}{D'} \tag{3}$$

where d is the thickness of the small intestine, and D' is the diameter of the converted inner intestinal surface's profile, and σ and p are the circumferential stress and the corresponding pressure at the azimuth θ, respectively.

For a rotational movement, the time t is the division of the azimuth θ by the angular velocity ω. Hence, (2) can be written to express the relationship between the stress σ and the rotating frequency f as follows:

$$\sigma(\theta) = \varepsilon(\theta)\left[E_1 \exp\left(-\frac{\theta E_1}{\omega\eta_1}\right) + E_2 \exp\left(-\frac{\theta E_2}{\omega\eta_2}\right) + E_3\right] \tag{4}$$

$$\omega = 2\pi f. \tag{5}$$

For every lateral cross section, the circumerferenital strain due to capsule insertion is determined by

$$\varepsilon = \frac{D_{\text{after}} - D_{\text{before}}}{D_{\text{before}} + d} \tag{6}$$

where D_{before} and D_{after} are the inner diamters of the intestinal tract before and after deformation, respectively. For the middle part with the spiral, D_{after} is equal to D'. For the frontal and rear parts without the spiral, only the contact areas are taken into account. Since these parts are semispheres, D_{after} varies with the axial position and can be calculated with the spherical radius, which is 5.5 mm.

The total normal load for one cross section can be obtained by using (3) to integrate the pressure along the circumference. Once the frictional coefficient μ is evaluated, the circumferential friction can be calculated with Coulomb's law of friction. Since the distance between the force and rotating axis is fixed, the rotational resistance can be solved in the form of a resistive torque. The equations are expressed as follows:

$$f = \mu \int p(\theta) d\theta \tag{7}$$

$$\tau = \frac{f D_{\text{after}}}{2}. \tag{8}$$

where f is the frictional force in the circumferential direction and τ is the resistant torque as a result of rotation.

TABLE I
IDENTIFIED PARAMETERS FOR THE SMALL INTESTINE SAMPLE 2

Parameters	Numerical Values
E_1 (kPa)	0.12
E_2 (kPa)	18.64
E_3 (kPa)	0.0122
η_1 (kPa s)	43.51
η_2 (kPa s)	0.2213

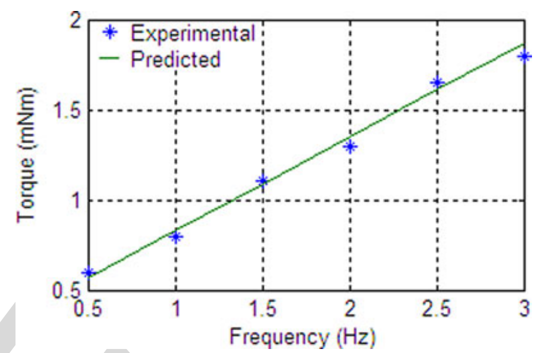

Fig. 10. Variation of the frictional torque with the capsule No. 2 rotating inside the small intestine Sample 2.

C. Parameter Identification and Model Validation

To identify the elastic modulus and viscosities in the model, a nonlinear least square optimization process is employed in this study. Based on the nonlinear relationship between the frictional torque and the rotating frequency, these material parameters were estimated by means of minimizing the summed square of the error vector with the experimental data presented earlier. A numerical search method, which is the interior-reflective Newton algorithm, was used to solve the problem. It acquires the approximate solution of a system by utilizing the method of preconditioned conjugate gradients at each iteration. It is suggested that this method is efficient for nonlinear optimization problems [24].

For the small intestine Sample 2, the measurements with the capsule No. 2 (helical angle $= 10^\circ$) was used to estimate the parameters. The numerical values are listed in Table I. The experimental and predicted frictional torques corresponding to the frequencies are shown in Fig. 10.

The measurements with the capsule No. 1(helical angle $= 5^\circ$) was used to validate the model for the small intestine Sample 2 shown in Fig. 11. With reference to these results, the estimated values are quite consistent to the experimental results, indicating that the analytical model is effective enough to predict the

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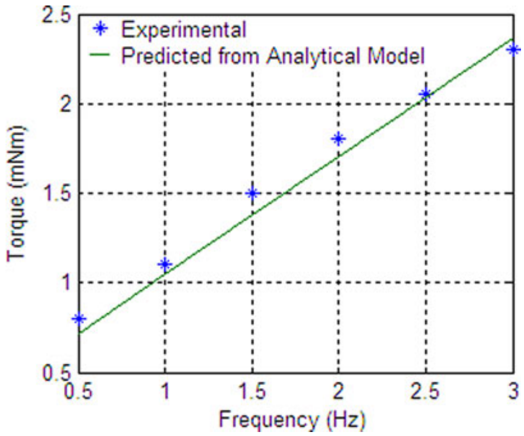

Fig. 11. Validation for the small intestine Sample 2.

TABLE II
IDENTIFIED PARAMETERS FOR THE SMALL INTESTINE SAMPLE 3

Parameters	Numerical Values
E_1 (kPa)	0.0348
E_2 (kPa)	0.7722
E_3 (kPa)	0.0448
η_1 (kPa s)	9.491
η_2 (kPa s)	0.2489

rotational resistance resulting from the spiral-type capsule rotating inside the small intestine Sample 2.

Though the trend of mechanical behavior is identical, the specific viscoelasticity of the intestinal tract may be different from one sample to another due to many experimental factors such as the freezing period, humidification level, and even variation in the tissue's microstructure. Therefore, the nonlinear least square optimization was repeated to identify the elastic modulus and viscosities of the model for the small intestine Sample 3. The measurements with the capsule No. 3 (helical angle = 15°) was employed. The estimated parameters are listed in Table II. The experimental and predicted resistant torque values are presented in Fig. 12. These results also demonstrate the efficacy of the analytical model in predicting the mechanical torque needed to overcome resistive effects associated with the viscoelastic intestine environment.

To evaluate the accuracy of the model for Sample 3, the measurements with other three capsules were compared to the predicted values with the estimated parameters, as illustrated in Fig. 13. With reference to these results, the model performs well when predicting the rotational resistance (i.e., torque) of the capsule No. 2 (helical angle = 10°). Though the prediction's accuracy is a bit lower for the other two capsules, the prediction is still in a reasonable range. We postulate that the discrepancy is possibly due to the effect of the stress concentration around the spiral structure, which is neglected in this model. In addition, the condition of the small intestine Sample 3 might slightly change during the tests due to a relatively longer experimental time compared to that with Sample 2.

From the estimated parameters for Sample 2 and Sample 3, it can be seen that the mechanical properties of different segments

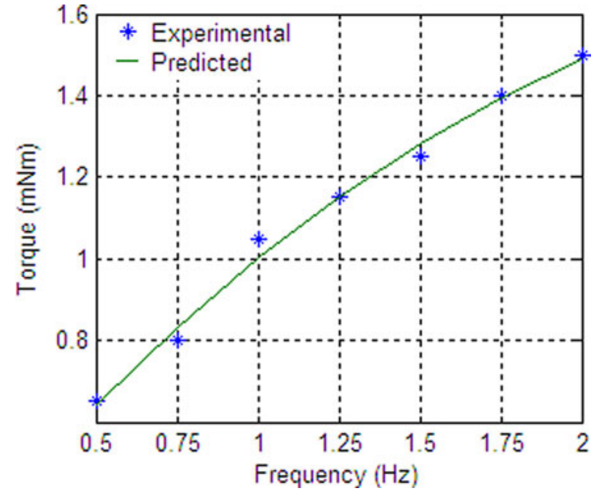

Fig. 12. Variation of the frictional torque with the capsule No. 3 rotating inside the small intestine Sample 3.

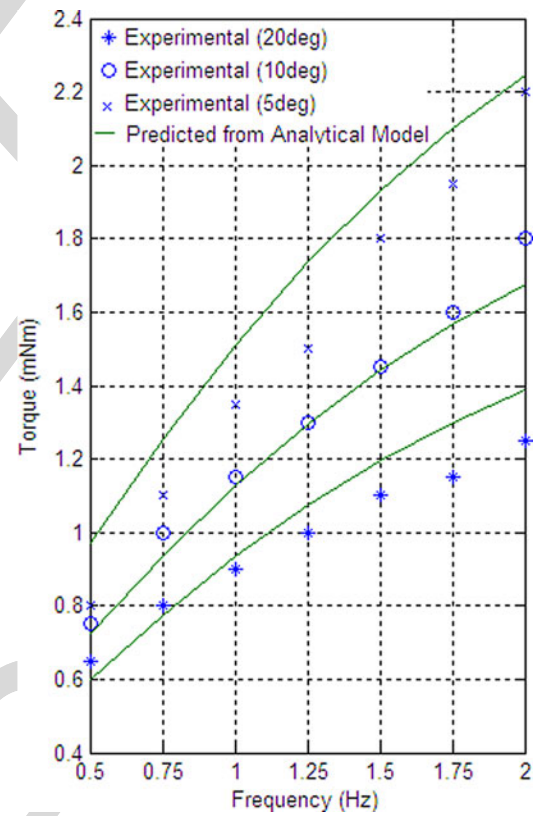

Fig. 13. Validation for the small intestine Sample 3.

(i.e., samples) exhibit some variance as expected, though they both show the viscoelastic properties and exert the rotational resistance in the same order of magnitude on the inserted capsule due to the deformation and rotation.

IV. CONCLUSION

The rotational resistance of a spiral-type capsule rotating inside the small intestine is investigated by both *in vitro* experiments and mathematical modeling and analysis, on which a limited literature is available. The experimental results show the viscoelastic nature of the intestinal tissue and the effects of various spiral structures and rotating speeds. At low rotating frequencies (0.5–3 Hz), a capsule (ϕ 11 $\times$ 26 mm) wounded with a 1-mm-high spiral works against a frictional torque varying from 0.5 mN·m to several mN·m. The torque increases with the increase of the frequency. Due to the same number of spiral in the tests, the helical structure with a smaller helical angle raises more in the lateral cross section of the robotic capsule, which results in more circumferential deformation of the small intestine and more rotational resistance. Viscoelastic properties of the "real" intestine are identified using a nonlinear optimization method. The validation results show that the proposed torque model is reasonably effective to estimate the rotational resistive torque of the small intestine. For different intestinal samples, though the rotational resistance is in the same order of magnitude, their biomechanical and tribological properties may show some variance due to the different conditions such as the duration of freezing time, intestine size, capsule weight, and humidification level. Both the experimental and modeling work provide a useful reference to characterize the required torque for a spiral-type capsule and, therefore, helps to undertake the design and optimization of the microrobots for medical use in the GI tract. However, before such a spiral-type robot is used in a real GI tract, *in vivo* experiments should be conducted in a highly unstructured, slippery, deformable, and nonsmooth environment to obtain a more accurate estimate of the rotational resistance.

Further work will aim to conduct more experiments with various intestinal specimens and improve the analytical model so that the stress concentration and viscoelastic properties due to variable-size spiral structures can be taken into account. Furthermore, some addition will be made to the current experimental setup so that a rotational and translational movement can be allowed between the capsule and the inner wall of the small intestine. The rotational resistance with different translational speed of the capsule will be investigated and compared to the current results.

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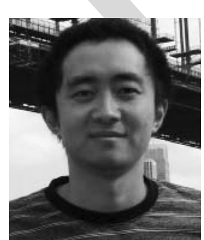

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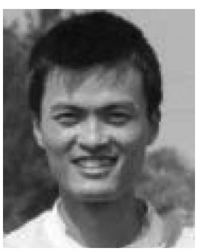

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