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Modeling and experimental investigation on the mechanical behavior of a spiral-type capsule in the small intestine

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Abstract

This paper reports on the study of the behavior of the viscoelastic contact between a spiral-type capsule and the small intestine. Both 2D and 3D simulations show that the traction force, which is due to the pressure difference between the two sides of the spirals, is velocity dependent. With an increase in the sliding velocity, the traction force decreases initially due to the reduced stress relaxation. However, if the velocity reaches some certain magnitude, the reduction in the stress becomes negligibly small. The traction force starts to increase because of the higher stress coming from the higher strain rates. The experimental torque and force measurements were taken for the capsules with different cross-section profiles. The results show that the traction force can be raised by carving grooves on the spirals' surface or using a higher and narrower spiral structure. The difference between the mechanical behaviors of a rotating-only capsule and a rotating-and-translating capsule were experimentally studied and explained in detail. The results show that a rotating-and-advancing capsule gets slightly more resistive torque than a rotating-only capsule.

Keywords

capsule, spiral, behavior, mechanical, investigation, experimental, modeling, intestine, type, small

Disciplines

Engineering | Science and Technology Studies

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Modeling and Experimental Investigation on the Mechanical Behavior of A Spiral-type Capsule in the Small Intestine

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***Abstract*— This paper reports on the study of the behavior of the viscoelastic contact between a spiral-type capsule and the small intestine. Both 2D and 3D simulations show that the traction force, which is due to the pressure difference on the two sides of the spirals, is velocity dependent. With the sliding velocity increases, the traction force decrease initially due to the reduced stress relaxation. However, if the velocity reaches some certain magnitude, the reduction of the stress relaxation becomes trivial. The traction force starts to increase because of the higher stress coming from the higher strain rates. The torque and force measurements are taken for the capsules with different cross-section profiles in the experiments. The results show that the traction force can be raised by carving grooves on the spirals' surface or using a higher and narrower spiral structure. The difference of mechanical behaviors of a rotating-only capsule and a rotating-and-moving capsule are experimentally studied and revealed as well. The results show that a propelled spiral-type capsule requires a slightly larger torque to main the rotation.**

I. Introduction

THe small intestine has always been the territory that is the most difficult one to explore for endoscopy. Three medical procedures have been developed to address this problem since early this century: double-balloon enteroscopy (DBE), spiral enteroscopy (SE) and wireless capsule endoscope (WCE) [1]. Among them, only WCE is able to inspect the entire small intestine and causes the least discomfort. It is considered as one of the greatest achievements in the field of minimally invasive medicine [2]. Since its advent in 2000 [3], WCE has been used as a routine procedure to diagnose lots of gastrointestinal (GI) diseases such as bleeding, celiac disease and Crohn's disease, many of which happens in the small intestine [4]. It is widely reckoned that WCE has got extensive potentials that can be fulfilled by being upgraded from a diagnostic-only tool to a powerful microrobot capable of carrying out not only diagnostic but also therapeutic tasks, such as non-invasive GI surgery and targeted drug delivery [5, 6]. To realize this, the very first step is to endow WCE with active locomotion in order to get rid of its reliance on the visceral peristalsis for movement in the intestinal lumen [7].

Mainly, two categories of approaches have been employed to provide WCE with maneuverability. The internal approaches [8, 9, 10, 11, 12] locate power and locomotion mechanisms onboard, which is able to bring very good movement control. However, more consumption of onboard space and limited energy usage are quite disadvantages for this type of mechanisms. These two concerns are the critical issues to a robot in micro or even smaller size. Therefore, the second type of approaches appears to be more promising for the application of a robotic capsule endoscope [7]. The external approaches employ an external magnetic field to actuate and propel a WCE with magnetic inclusions. One of the magnetic propulsion mechanisms is direct pulling, which produces an external magnetic gradient field to exert a direct pulling force on the capsule [13, 14, 15]. The second feasible way is using a rotating external magnetic field to generate a magnetic torque for the magnetic capsule with a spiral structure wound on its surface. Due to the interaction between the spiral and the intestinal wall, the rotation can be converted to a linear movement for effective propulsion [16, 17, 18, 19]. Since creating high magnetic field gradients is more difficult than creating high magnetic fields [2], this second mechanism of magnetic propulsion seems more promising if a relatively large distance is required between the power source and the microrobot, e.g., the case of treating patients with obesity. To develop an efficient spiral-type capsule, it is significant to design and optimize the capsule's topology, including the capsular body and the spiral structure. Therefore, it is necessary to obtain a good understanding of the behavior of the contact between the capsule and the intestinal tissue, reportedly as a viscoelastic material [20].

In this study, both finite element (FE) modeling and experiments are conducted to investigate the behavior of the viscoelastic contact between a spiral-type capsule and the small intestine. Both the 2D and 3D simulations show the velocity-dependence happens not only to the sliding friction but also to the traction force, which is due to the pressure difference on the two sides of the spirals. With the sliding velocity increases, the stress relaxation of the intestine across the spirals decreases, which makes the traction force decrease initially. However, if the velocity reaches some certain magnitude, the reduction of the stress relaxation becomes trivial. The traction force starts to increase because of the higher stress coming from the higher strain rates. The torque

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and force measurements are taken for the capsules with different cross-section profiles in the first set of experiments. It is shown that the traction force can be raised by carving grooves on the spirals' surface or using a higher and narrower spiral structure. In the second set of experiments, the difference of mechanical behaviors of a rotating-only capsule and a rotating-and-moving capsule are studied and revealed. The results show that a propelled spiral-type capsule requires a slightly larger torque to main the rotation. Both the modeling and experimental works bring benefits to the better understanding of the spiral-type capsule's mechanical behavior inside the intestinal lumen and help the design and optimization of the whole robotic system for the propulsion of an active endoscopic capsule.

II. Modeling of Intestine-Spiral Contact

A. Assumptions and general setup

Finite element (FE) simulations are conducted to theoretically investigate the viscoelastic contact between the small intestine and a spiral-type capsule. A commercial software package, ABAQUS, is used to carry out the FE analysis, for which some assumptions are made as follows:

1. The intestinal wall is very soft compared to the outer surface of the spiral-type capsule. Therefore, the interaction between them barely causes deformation to the latter, which is assumed to be a rigid object.
2. Since the impact on the viscoelastic contact from the capsule's topology is the major concern of this study, the weights of both the capsule and intestine are not considered.
3. The intestinal tissue is assumed to be an incompressible, homogeneous and isotropic material. Besides, the intestine is assumed to be a symmetrical tube, with a uniform wall thickness.

The stress relaxation data and the stress-strain relation from the measurements of Ref. [21] is employed to define the hyperelastic and viscoelastic properties of the small intestine. Both of the intestine's ends are fixed. The spiral-type capsule's outer surface is set as the master surface while the intestine's inner wall is set as the slave surface. These two surfaces consist of the contact pair. As the capsule moves, it causes deformation of the intestine, which consequently generates the reaction force.

B. Velocity-dependent reaction force

When a spiral-type capsule is rotating inside the intesitnal lumen, the viscoelastic contact produces two forces for the whole capsule. The first one is the sliding friction, which is always tangential to the interacting surface and against the direction of motion. This sliding friction happens to both the regular capsular body and the spiral structure. It only leads to resistance and brings no benefit to the propulsion. The other force is due to the intestinal tissue's hoop stress responding to the deformation, which is always normal to the contacting surface. The hoop stress of the intestine generates pressure distributing all around the whole capsule. The pressure on the regular capsular body always points to the axis of the capsule. Therefore, it only brings compression to the capsule and does not generate any traction force. However, the pressure on the spiral structure results in different impact. As is seen in Fig. 1, the spiral slides on the intestine and the contact causes stress in the tissue. The tissue interacts with the right-hand side of the spiral first and then moves gradually to the left-hand side. Due to the stress relaxation, the stress at the first contact is the largest and decrease then, which exerts the spiral's right-hand side higher pressure than its left-hand side. Subsequently, this pressure difference produces the net force perpendicular to the spiral. The circumferential component contributes to the resistive torque and the axial component is what is desired: the traction force.

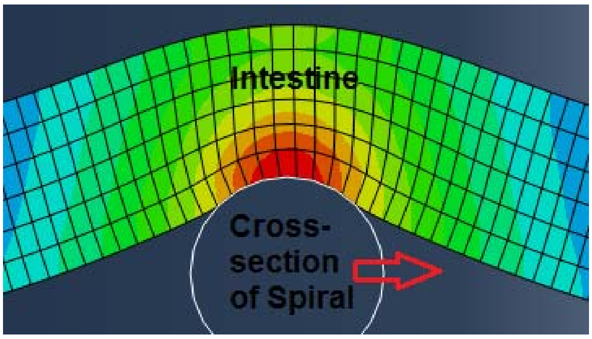

Fig. 1. The spiral sliding across the intestine in the 2D FE simulations.

The coulomb's law of friction ($f = \mu N$) indicates that the sliding friction is related to the COF (coefficient of friction) of the interface and the normal force as well. This normal force on the capsule's surface is led by the pressure as a result of the hoop stress of the intestine. Apparently, the stress is velocity-dependent. If the capsule spins in the intestine fast, less stress relaxation will occur. This gives rise to more stress for the intestine and correspondingly higher pressure on the capsule's surface. Therefore, the sliding friction is raised.

The 2D FE simulations are conducted to study the velocity-dependent reaction force on the spiral structure. The configuration is as described in Fig. 1. The cross-section of a spiral deforms the intestine and slides along it. The simulation result is shown in Fig. 2 that the sliding friction increases when the velocity is raised. However, this increment slows down as the velocity keeps increasing. This trend is

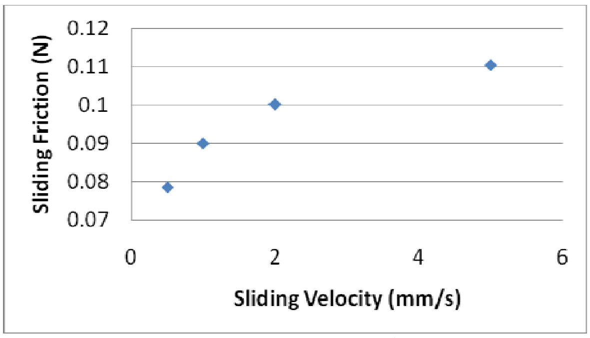

Fig. 2. The relationship between the sliding friction and the sliding velocity.

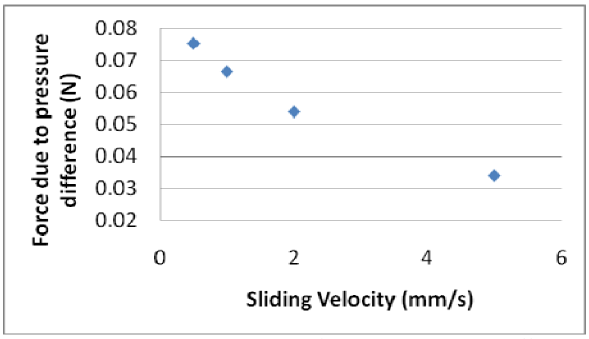

Fig. 3. The relationship between the force due to pressure difference and the sliding velocity, relatively low velocity.

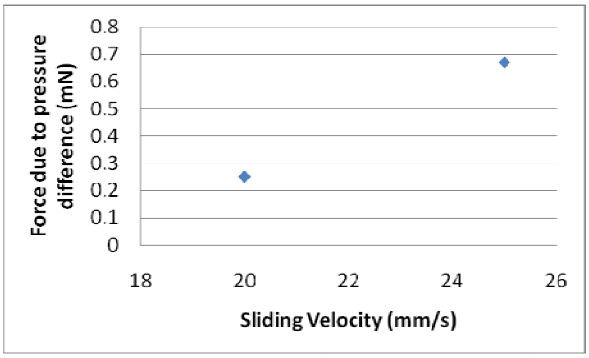

Fig. 4. The relationship between the force due to pressure difference and the sliding velocity, relatively high velocity..

consistent with our previous study [22]. As discussed above, the net force from pressure difference of the spiral's two sides contributes to the traction for the capsule. Though its circumferential component also contributes to the resistive torque, this net force is still desired to be as large as possible in order to provide enough traction for the capsule. From the simulation result in Fig. 3, it is shown that it is velocity-dependent as well. As the spiral's sliding velocity rises from 1 mm/s to 5 mm/s, this net force decrease because less stress relaxation is caused by the faster movement, which makes the pressure difference reduced under this condition. However, increasing the velocity does not always decreasing the pressure difference. As is known, the stress relaxation is quite rapid initially and then become less and less. Therefore, once the veloctiy reaches some certain point, the stress relaxation does not differ much at different velocities. Meanwhile, since the high velocity causes large strain rate and subsequently large stress in the tissue, the pressure at the spiral's right hand side becomes high. As the stress relaxation does not decrease much, with the furhter rise of velocity, the increased strain rate gives rise to increased pressure and consequently the increased net reaction force. This is indicated by the simulation result, shown in Fig. 4.

C. 3D simulations

The 3D FE simulations are conducted to model a spiral-type capsule rotating and contacting the viscoelastic intestine. The inner diameter and the thickness of the intestine are 11.7 mm and 1mm, respectively, which are the average values from the measurements of the real intestinal samples.

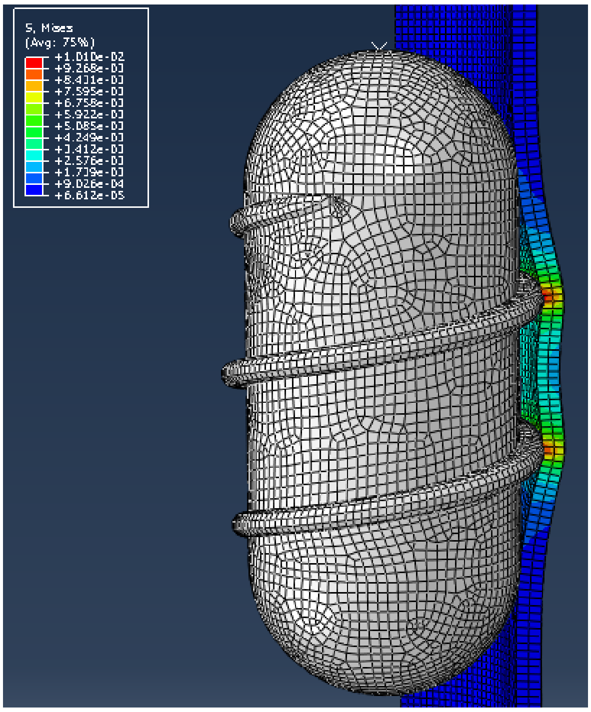

Fig. 5. The model in the 3D FE simulations.

TABLE I
THE TORQUE AND FORCE PREDICTION IN THE 3D SIMULATIONS

Conditions	100% Slip		No Slip	
	Torque (mNm)	Axial force (mN)	Torque (mNm)	Axial force (mN)
COF0.6, 1Hz	0.211994	0.0896734	0.211983	-4.33759
COF0.6, 2Hz	0.212353	0.0805985	0.212232	-4.43261

The spiral-type capsule has got the capsular body based on the size of Pillcam SB2 capsule (Given Imaging) and the spiral's height is 1mm. The configuration of the model is shown in Fig. 5.

The similar model was used to investigate the resistive torque and traction force of different spiral-type capsules in our previous work [23]. However, in that study, the capsule only rotates at the same position. In a real case, a propelled capsule should have got both rotation and translation. Therefore, it is necessary to study the difference between the case with only rotation and the case with both rotation and translation. In this study, a spiral-type capsule with the helical angle of 10° is simulated. The modeling results are shown in Table 1. In the case of 100% slip, the net axial force is the traction force because the there is no sliding friction in the axial direction. It is seen that, with the rotating frequency raised from 1 Hz to 2 Hz, the resistive torque increases but the traction force decreases. This agrees with the 2D analysis discussed above. If the rotating frequency increases to some certain value, the traction force is postulated to start increasing. In the case of no slip, the axial force is the net amount of the traction force and the axial sliding friction. Since the translational velocity is large, the axial sliding friction is much larger than the traction force, making the net axial force negative. In this extreme case of no slip, there is no intestine getting across the spiral, which leads to no pressure difference between the two sides of the spirals. Hence, theoretically, there is no traction force on the spiral in the case of no slip. Also, the circumferential component of the net reaction force is equal to zero as well. Therefore, the resistive torque is reduced when the capsule is propelled without slip, shown by the simulation result in Table 1.

III. TORQUE AND FORCE MEASUREMENTS

A. *Experimental Setup*

Fig. 6. The endoscopic capsules wound with spirals.

Experimental measurements are carried out to measure torque and force of a rotating spiral-type capsule inside a real small intestinal segment. A segment of brass wire is wound on the surface of a dummy Pillcam SB2 (Given Imaging), acting as the spiral structure. A few capsules of such kind are shown in Fig. 6. A steel rod is attached to one end of the capsule and then is mounted to the torque/force sensor for acquiring measurements. In our previous works [22, 23], the resistive torque and traction force were measured by using this approach. However, the situation is the same as the modeling work. The measurements were taken as the capsule did not have translation movement. Therefore, in this study, the experimental setup is upgraded to allow the capsule to have rotation and translation (relative to the intestinal tract) at the same time. The assembly of sensor-rod-capsule is fixed to the tip of a robotic arm, which is able to provide any translational movement to the capsule at will. The general setup for the torque measurements is shown in Fig. 7. When performing the force measurements, the torque sensor is replaced by the force sensor capable of getting both compressing and stretching forces.

B. *Experimental Procedures*

In the first set of experiments, the torque and force measurements are taken with four different spiral-type capsules as shown in Fig. 6. All the capsules have the spirals with the same helical angle, 10°. The only difference of their spiral structures is the cross-section in order to find out the effect of the cross-section profile of a spiral. All the spirals are made of 1mm brass wires. However, the first one (from left) is compressed. Hence, the spiral is a bit wider but has a slightly smaller height (~0.8mm). The second spiral is not deformed. But a couple of grooves are cut on its surface. The third one is the smooth and regular wire. The last one is a

Fig. 7. General view of the experimental setup.

deformed wire as well. But this spiral has the increased height (~1.2mm) but the decreased wideness. The measurements are only taken when the capsules are rotating without translation. The rotating frequency is 1Hz.

In the second sets of experiments, only the capsule with the smooth regular spiral is tested. The robotic arm is employed to generate a translational movement for the capsule when a constant-speed rotation is provided to the intestinal tract. Thus, both rotation and translation are produced when the viscoelastic contact happens. The rotating frequency is set to be 1 Hz for all the tests of this set while several different translational velocities are employed. Therefore, the measurements are taken when the capsule is under different slipping conditions.

As for the intestinal specimens, the porcine small intestine is adopted since it is reported to be quite close to a human being's intestine regarding the biomechanical property [24]. Before the experiments the specimens are immersed in the physiological saline to avoid tissue rupture. One specimen is used for one set of tests. For each set, the experiments are conducted quickly in order to make sure the measurements are taken with the similar condition of the intestinal sample.

C. *Results and Discussions*

1) *Effects of the different cross-section profiles*

TABLE II
THE TORQUE AND FORCE MEASUREMENTS FOR DIFFERENT SPIRAL CROSS-SECTION PROFILES

Spiral Cross-sections	Resistive torque (mNm)	Traction force (mN)
Regular and smooth	2.2	20
Regular, grooved	2.7	23
Deformed, decreased height	2.2	17
Deformed, increased height	2.5	22

The results regarding the effects of the different cross-section profiles are shown in Table II. Since the capsules are not provided with translational movement, there is no sliding friction in the axial direction. Therefore, the force measurements indicate the traction forces the capsules obtain because of the pressure differences between the two sides of the spirals. From the results, it is seen that the deformed cross-section profile with the reduced height performs worst. Compared to the regular and smooth one, its resistive torque remains the same and its traction force decreases, which mean it will require the same magnetic torque to get effective rotation but produce less propulsion force. Hence, the wider but lower spiral cross-section is a bad option for propulsion. The other two modifications to the 1mm wire suggest the similar effects. With the grooves, the spiral generates more traction force while the resistive torque also increases at the same time. The narrower and higher spiral cross-section gives rise to the increased traction force and resistive as well, compared to the regular and smooth spiral. If enough magnetic torque is accessible for the spiral-type capsule, apparently, larger traction force is desired so that the capsule will be able to overcome the axial sliding friction led by its advancement in the intestine.

2) Measurements with rotation and translation

When the intestinal tract is spinning anti-clockwise and the capsule is moving linearly in its axial direction, the two

TABLE III
TORQUE MEASUREMENTS FOR ROTATING-ONLY AND ROTATION-TRANSLATION CAPSULES

Capsule moving direction and translational velocity	Resistive torque (mNm)
Capsule only spin, 0mm/s	0.7
Capsule go down, 1mm/s	0.8
Capsule go down, 3 mm/s	1
Capsule go up, 1mm/s	0.65
Capsule go up, 3mm/s	0.6

modes of the relative interactions between the intestine and the capsule are shown as the schematic diagram in Fig. 8. The torque measurements are taken when different translational velocities are used for the capsule (helical angle = 5°). The results are shown in Table III.

In practice, if the intestinal tissue comes from the left-hand side to the right-hand side, the propulsion direction for the spiral-type capsule should point downward as the first configuration in Fig. 8. From the results, it is seen that the resistive torque slightly increases when the capsule is propelled (downward), compared to the case that it is only spinning without translation. When the translational velocity is raised further from 1mm/s to 3mm/s, the torque even becomes larger. Though the second mode in Fig. 8 can't happen in real propulsion, the measurements are still taken to investigate the impact of the capsule's translation on behavior of the viscoelastic contact. It is seen that the torque is slightly reduced when the capsule is provided with the upward linear movement. Here, we postulate the possible explanation for this phenomenon. For a right-hand-spiral caspule, between A and B is the route through which the intestin passes the spiral in Fig. 8. If the capsule doesn't have linear movement, the route is the blue line. When the capsule goes down, the route becomes longer, which means that it takes more time for the intestine passes the spiral. Due to the stress relaxation, the

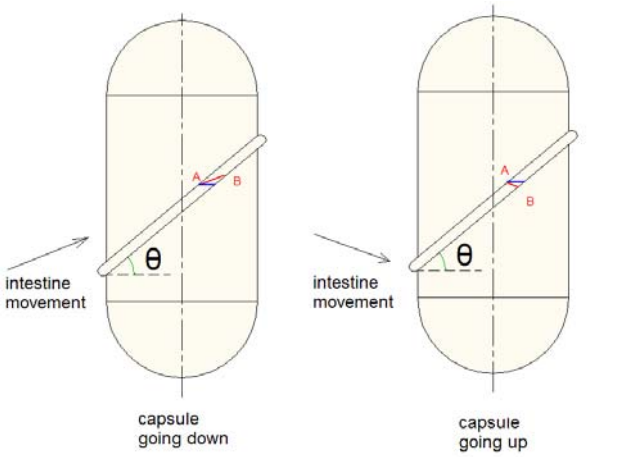

Fig. 8. A right-hand-spiral capsule with the translation and the intestine with the anti-clockwise rotation

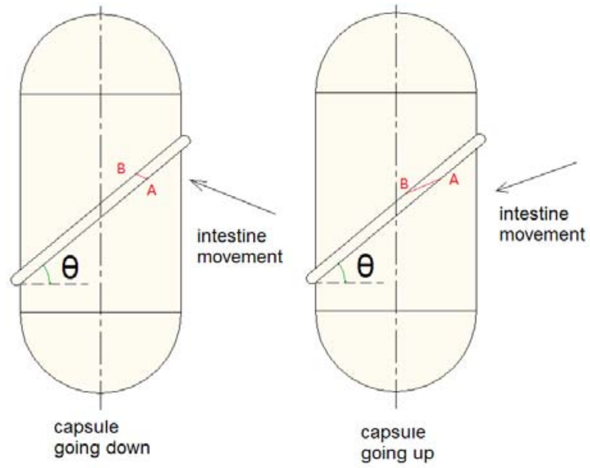

Fig. 9. A right-hand-spiral capsule with the translation and the intestine with the clockwise rotation.

pressure drops more at the other side of the spiral. More pressure difference between two sides of the spiral leads to more torque. When the capsule moves up, the route becomes shorter and less stress relaxation of the intestine causes less pressure difference and less torque consequently.

The clockwise rotation is also carried out to the capsule afterwards. When the intestine comes from the right-hand side to t left-hand side, the propulsion direction is upward in reality, which is the second mode in Fig. 9. The measured torque in the second mode is slightly larger than that when the capsule is only rotating without translation. This can also be reasonably explained by the above discussion, which further supports the rationality of our postulation.

IV. CONCLUSION

Both modeling and experimental efforts have been made to investigate the behavior of the viscoelastic contact between a spiral-type capsule and the small intestine.

The finite element (FE) analysis shows that, not only the sliding friction but also the traction force from the pressure difference on the spiral are velocity dependent. When the sliding velocity increases, the sliding friction increases while the force due to pressure difference decreases initially. This is because the stress relaxation of the intestine is reduced, which causes the larger pressure on the robotic body but makes the pressure difference on the spiral smaller. When the velocity approaches some certain value, the reduction of stress relaxation is very little. Since the higher strain rate produces the higher stress, the force due to pressure difference starts to rise higher pressure on the spiral. Both the 2D and 3D simulations indicate this trend of velocity-dependence of the viscoelastic contact.

Torque and force measurements are conducted to study the effect of the cross-section profiles of the spirals. From the results, it suggests the traction force can be enhanced by carving grooves on the spirals' surface or adopting the higher spirals. The experiments are also carried out to investigate the resistive torque when a spiral-type capsule has both rotational and translational motion in the intestinal tract. The results show that a slightly larger torque is generated to the propelled capsule since the translation causes the increased stress relaxation of the intestinal tissue across the spiral structure.

Further work will aim to perform more FE simulations and experiments with various spiral structures to find out the optimized configuration for the propulsion of a spiral-type capsule working inside the small intestine.

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