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Experimental investigation of intestinal frictional resistance in the starting process of the capsule robot

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ABSTRACT

The imperfection of the intestinal friction model is one of the biggest obstacle of the capsule robot's development. This paper seeks to study the intestinal frictional resistance in the starting process of the capsule robot. Experiments are conducted to measure actual frictional resistance, which is found to have something to do with the velocity, acceleration and original state of the capsule robot. The analytical expression of the frictional resistance can fit the experimental result with R-square equaling 0.9605. The achievement of the article is hoped to smooth the motion and save the energy in the capsule robot's starting process.

1. Introduction

Broad challenges exist when fundamental research to study frictional characteristics between medical device and biological tissue is no exception. Capsule robot, which can examine the whole gastrointestinal (GI) tract non-invasively and actively when performed by doctors who have had special training and are experienced in the endoscopic procedures, is one of the most representative medical devices. The imperfection of friction model between the capsule robot and the intestine has been one of the biggest obstacles of the development of the capsule robot [1]. The capsule robot needs to start and stop frequently when working in the intestine. The frictional resistance increases rapidly from a small value in the robot's starting process [2]. If the driving force of the capsule robot in uniform motion is used in accelerated motion, the capsule robot cannot move smoothly and more energy is wasted.

The study aims to figure out the intestinal frictional resistance variation in the starting process of the capsule robot when the capsule robot moves inside the intestine. Some experiments are conducted to measure the actual frictional resistance with a homemade uniaxial experiment platform. The frictional resistance is found to changes with the capsule's velocity, acceleration and original state. Further, curve-fitting is used to deduce the analytical expression of the frictional resistance in the starting process. The validity of the fitting result is verified by experiment result. The achievement of this study is hoped to make certain the intestinal frictional characteristics in the starting process of the capsule robot and optimize the control method of the capsule robot with various driving principle.

2. Background

According to the statistics of World Health Organization (WHO), there are nearly 130 million patients with GI tract disease in China. More people have suffered with the disease in the worldwide. The capsule endoscopy (CE) has been the most effective medical device to examine the GI tract painlessly and non-invasively. CE has become the gold standard for the diagnosis of most diseases in the GI tract [3–6]. However, the passive feature of CE makes it out of control in the intestine. Missed diagnosis and ileus will occur possibly during an 8-h inspection [7]. To improve the situation, many researchers are engaging in developing an active CE, which can be called capsule robot, using various driving mechanisms [8–16]. Before a practicable solution can be devised, the frictional characteristics between the capsule robot and the intestine need to be researched.

Now one of the main limitations that the capsule robot moves in the intestine inefficiently is the imperfection of the friction model due to the presence of complex lumen surface features and

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a highly motile, tortuous intestine path. The frictional resistance comes from intestinal peristaltic contractions, mucoadhesion, the collapsed lumen and the interaction between the capsule surface and the intestinal inwall [17]. The surrounding organs, weight of the intestinal wall and pressure from the fluid within the intestine also impart forces on the capsule robot. The uncertainty of frictional characteristics has been the main obstacle of the development of the capsule robot.

Experimental investigation is the main method to research the frictional resistance between the capsule and the intestine. Some people focus on the affection of the capsule's parameters, while others seem more concerned with the material property of the intestine. The characteristics of the capsule, such as weight, shape, dimension, material, contour line, surface preparation methods and kinestate have great influence on the friction [18–24]. Researches show that the friction of smooth cylindrical capsule is smaller than other shapes [18,19], the influence of the capsule's length on the friction is greater than that of the diameter [21], capsule's weight has no significant effect on the friction [22], resin material is suitable for making capsule's shell [20] and the friction are in direct proportion to the capsule robot's velocity [23]. The biomechanical properties of the intestine also have a great influence on the capsule's movement. Hoeg et al. studied the tissue distention of the intestine when a robotic endoscope moved through. An analytical model and an experimental model were developed to predict the tissue behavior in response to loading [25]. Ciarletta et al. used the theory of hyperelasticity to make a stratified analysis of the intestinal wall. The hyperelastic model is significative to research the frictional characteristics of the intestine, but it neglects the time effect [26]. Woo et al. considered the friction of the intestine using a thin walled model and Stokes' drag equation. However, the model cannot fully describe the material characteristics of the intestine [27]. Kim et al. found that the variation of resistance was correlated with the viscoelasticity of the intestine. A five-element model is used to describe the viscoelastic property of the intestinal stress relaxation. Furthermore, the group first developed an analytical model for the friction prediction, which was verified by finite element analyses [28].

Most of the above experiments are conducted in the state of rest or uniform motion. However, the frictional resistance in the starting process has been neglected by most of the researchers until now. Therefore, there is hardly any appropriate control method aiming at the starting process. By indentifying the parameters that can be manipulated dynamically, a well-designed capsule robot can work with or against the friction as needed for movement or positioning. Tubular porcine intestine is chosen as the experimental subject, which is pretreated to maintain the biomechanical characteristic. A homemade uniaxial experiment platform is used to conduct the experiment. An analytical expression of the frictional resistance will be deduced according to the experimental results. This work is hoped to change the status quo that the capsule robot's frictional resistance is uncertain in the starting process and guide the design of capsule robot's starting mode.

3. Experimental methods

A homemade uniaxial experiment platform was developed to test the frictional resistance variation in the starting process. The platform consists of two parts: drive unit and data acquisition unit, as shown in Fig. 1. The main part of the drive unit is LMX1E series linear motor system, which is produced by HIWIN. The positioning accuracy of the system can reach ± 1 μm. The left side of the drive unit is a load platform. The rotor of the linear motor is combined with a support, on which there fixed a one degree of freedom micro force sensor (FUTEK LSB200), whose accuracy is 1 mN. The probe of the force sensor is connected to a capsule dummy that is placed inside the intestine with a polymer string. The capsule dummy can be pulled by the drive unit with different velocities and accelerations. Flexible polyurethane foam (PUF) is used as the basement to support the intestine. This way can simulate an in vivo environment of the intestine as much as possible. PCI 6229 data acquisition (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.

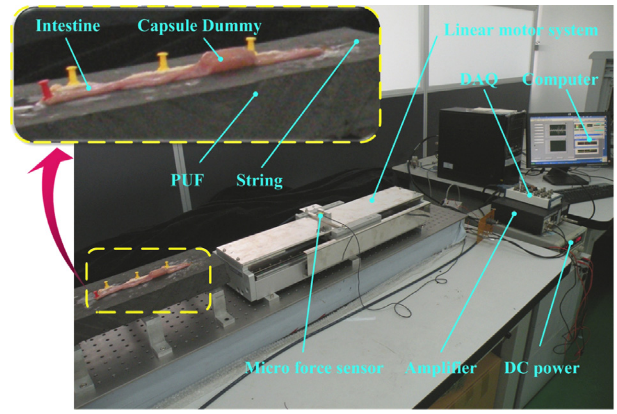

Fig. 1. Experiment platform for measuring frictional resistance variation.

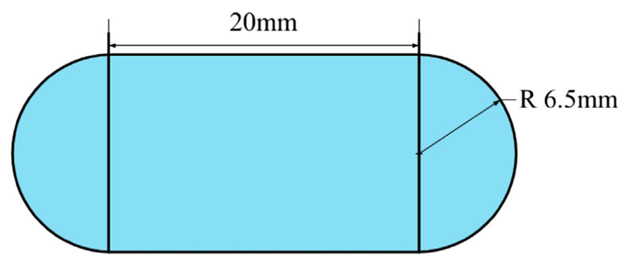

Fig. 2. The dimensions of the capsule.

The capsule dummy used in the experiment is made of resin material. The shape of the capsule dummy is an assembly of a cylinder in the center and two hemispheroids in both ends. The dimension is shown in Fig. 2. The weight of the capsule inside the intestine is 3.9 g.

The intestine used in the experiment was taken from a standardized laboratory pig to ensure the repeatability of experimental results. In order to reduce the effect of the food debris within the intestine, the pig was kept off food, but not water for 24 h. Under the supervision of the medical ethics committee, the pig was sacrificed with an anesthetic overdose and anatomized by professionals. Segments of jejunum were excised from the pig immediately following euthanization and stored in a sink that is filled with 37 °C Tyrode's solution with continual oxygen supply (1000 ml Tyrode's solution consists: NaCl 8.0 g, KCl 0.2 g, $MgSO_4 \cdot 7H_2O$ 0.26 g, $NaH_2PO_4 \cdot 2H_2O$ 0.065 g, $NaHCO_3$ 1.0 g, $CaCl_2$ 0.2 g, glucose 1.0 g.). When exposed to unconditioned air, intestinal tissue drying had been observed and previously remedied by applying saline to the tissue surface [29]. Because of lack of constant temperature and humidity system in the experiment platform, changing same type test specimens frequently is adopted to ensure the mechanical property of the test specimen. The mesentery and one side of the intestine specimen are fixed on the basement.

The drive unit is controlled to pull the capsule with different velocities and accelerations. The polymer string is adjusted to a