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Frictional resistance model for tissue-capsule endoscope sliding contact in the gastrointestinal tract

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ABSTRACT

Wireless capsule endoscopes are becoming prevalent in the medical field as screening, diagnostic and therapeutic tools within the gastrointestinal (GI) tract. However, state-of-the art capsules lack active locomotion systems, which could improve accuracy and broaden applications. The actuation efficiency for direct capsule-tissue contact depends on the frictional resistance between the capsule and the intestinal wall. A model for predicting the resistance force on a capsule was developed and experimentally validated by performing drag force experiments using various cylindrical capsule design parameters and tissue properties. Of the design parameters studied, capsule edge radius influences frictional resistance the most. The average normalized root-mean-square error between the model and experimental results is 6.25%. These results could lead to optimized capsule endoscope actuation systems.

1. Introduction

In recent years, wireless capsule endoscopes (WCEs) have become commercially available and a popular topic of research in the diagnostic robotics field. State-of-the-art WCEs are gaining popularity as a screening tool within the gastrointestinal (GI) tract to aid in the diagnosis of diseases, such as colorectal cancer (CRC) and inflammatory bowel disease (IBD). Colorectal diseases, and in particular CRC, affect a large number of people worldwide, with a strong impact on healthcare systems. It was estimated that 137,000 people will be diagnosed with CRC in 2014 (8.5%, or 3rd in incidence ranking, of all new cancers) in the U.S., resulting in approximately 50,000 deaths (8% of all cancer deaths), making it the 3rd deadliest cancer [1]. Additionally, CRC ranks fourth in terms of incidence rate among all cancers in high-income countries, accounting for 608,000 deaths worldwide in 2008 [2]. Fortunately, there is a 90% 5-year survival rate if CRC is detected at the earliest stage (confined to a primary site) [1]; however, the 5-year survival rate drops to 13% if CRC is detected after the cancer has metastasized [1]. Only 40% of CRC cases are detected in the earliest stage, in part due to the under-use of screening [1]. Therefore, regular screening is highly recommended for patients older than 50 years or who have a family history of CRC. An adequate screening procedure is one which allows for the detection and removal of colorectal polyps before progression to cancer [1]. The potential benefit of cancer screening, a life-saving procedure, can be achieved if accuracy and reliability are high throughout the screening procedure. A rise in screening procedure prevalence has been linked to both incidence and death rate declinations [1]. Therefore, reliable regular screening methods are imperative to early stage CRC diagnosis.

WCEs are a promising technology for CRC screening because they are non-invasive and compact, resulting in a painless and accessible option for patients. However, there are several drawbacks to commercially available designs which render them inferior to the clinically preferred endoscopic methods. WCEs rank relatively low in diagnostic accuracy due to their passive nature. They are also limited to exploratory procedures as they do not have tools for therapeutic procedures, such as drug delivery or biopsies. One method of addressing these drawbacks is to implement an active position control method. By actively controlling WCEs, accuracy is improved due to the ability to position and orient the capsule, and return to abnormal areas for secondary diagnoses. Additional capabilities could also be added to a soft-tethered capsule [3] with a working channel, such as irrigation, insufflation, and tools for biopsies and drug delivery. The major drawback of implementing locomotion for WCEs is the increase in complexity and size of the system.

Several actuation methods for WCEs are under development, including legged [4], treaded [5], inch-worm [6], magnetic [7–9]

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and hybrid [10] systems, all of which require dragging the capsule through the GI tract. A comprehensive discussion on capsule endoscope locomotion methods can be found in [11].

Knowing the resistance force on the capsule from the surrounding tissue is imperative for an effective, efficient and safe design. The model developed in this paper provides accurate prediction of the force required to drag a WCE through the GI tract when the capsule is in partial contact with the GI wall (*e.g.*, in the insufflated colon or stomach). A typical problem setup is presented by using a magnetic actuation system as an example, followed by the model development. A pilot study is performed on excised porcine colonic tissue to validate the model with respect to each capsule design parameter (edge radius, length, diameter, normal force and velocity) and to determine which parameter affects the drag force the most. Then, an in depth study is performed on excised colonic porcine tissue of that parameter (edge radius). Finally, a study is carried out to validate the model in all regions of the GI tract (esophagus, stomach, small bowel, and colon).

2. Background

For the purpose of presenting a potential application for the model and for determining realistic test values, a magnetically actuated WCE system is considered. However, it is important to note that the model and experiments were designed in such a way to be applicable to any system where a cylindrical capsule is moved across a tissue substrate.

Magnetic actuation of WCEs is a promising locomotion method in development, and employs magnetic coupling between an external magnet (located outside of the patient) and an internal permanent magnet (IPM) located inside the capsule [12]. The external magnet is generally fixed to and manipulated by an external robotic arm in order to guarantee higher stability for steering, and can be either an external permanent magnet (EPM) or an electromagnet. Several groups have developed complete EPM systems [9,13,14] and electromagnetic systems [15–17] including a system which uses magnetic resonance imaging (MRI) to control the capsule endoscope [18]. A typical setup of a magnetic actuation system using an EPM is summarized in Fig. 1a. An IPM is added to a typical WCE and placed in the GI tract. The WCE is attracted to the EPM, but is constrained by the intestinal wall and surrounding organs. The EPM can be positioned and oriented to induce a magnetic field $\vec{B}$ and a magnetic field gradient $\nabla\vec{B}$ which impose forces and torques on the IPM within the capsule.

Locomotion is achieved when Eqs. (1) and (2) are satisfied.

$$F_M = F_{\nabla \vec{B}_y} = F_W N \qquad N \geq 1 \tag{1}$$

$$F_D = F_{\nabla \vec{B}_x} \geq F_R = F_x + F_A + F_f \tag{2}$$

where F_M is the vertical attraction force due to the magnetic field gradient, $\nabla\vec{B}_y$, F_W is the weight of the capsule (*i.e.*, the force on the capsule due to gravity), F_D is the drag force due to the magnetic field gradient, $\nabla\vec{B}_x$, F_R is the resistance force on the capsule, and N is a design factor. N must be at least 1 to overcome the weight of the capsule. When N is larger than 1, a normal force F_N is introduced into the free body diagram in Fig. 1a. N is manipulated by changing the magnetic attraction force, which can be achieved by altering the strength of the magnets (IPM or EPM), or changing d_y. The resistance force, F_R, is a summation of forces opposing the drag force, F_D, and includes friction (F_f) and pressure on the front of the capsule due to deformation of the tissue (F_A and F_x). As long as tissue deflection δ_{max} is non-zero or $h > 0$, F_x exists and is equal to the integration of the horizontal component of the stress

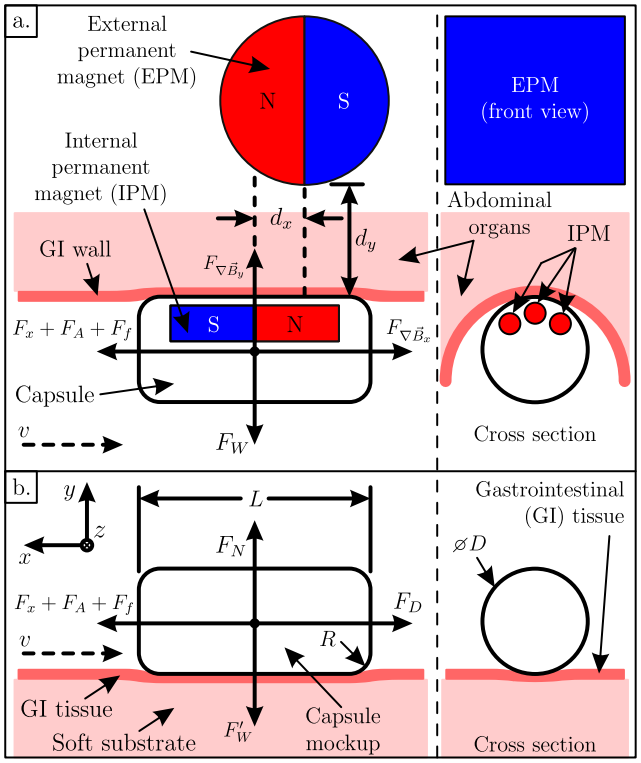

Fig. 1. (a) A simplified typical setup of a magnetically actuated system using an external permanent magnet, and (b) the free body diagram of the bench top tests where a capsule is placed on GI tissue and a soft substrate (Sim*Vivo, LLC, Essex, NY).

over the contact area. F_A only exists when $(h+\delta_{max}) > R$, and is due to pressure from the tissue on the flat front face of the capsule.

The general magnetic setup depicted in Fig. 1a can be translated into a bench top configuration and represented as the free body diagram depicted in Fig. 1b by assuming equivalent normal forces:

$$F_N = F'_W = F_{\nabla \vec{B}_y} - F_W = (N-1)F_W \tag{3}$$

where F'_w is the adjusted weight of the capsule mockup to simulate the normal force of the magnetic capsule against the inside surface of the bowel.

The aim of this paper is to develop a general model, and as such the magnetic scenario is only one example application. For this reason, some details about the magnetic system have been omitted from this work. A detailed discussion on magnetic theory and locomotion can be found in [9] and [19].

Others have evaluated various capsule parameters in GI tribology studies, but only one [20] to the authors' knowledge which addressed capsule edge radius. However, only 3 experimental data points were presented in [20] without comparison to a model. The study presented in this paper offers a general model for capsule locomotion system design and an in depth analysis on the effect of edge radius. Others have extensively studied the effect of capsule diameter, length, speed, normal force, and velocity, all of which were studied to assess model validity in this work. In summary, literature reports that resistance force is directly proportional to capsule speed [21–29], diameter [20–24,29,30], length [23,29,30], and normal force [21,23,31].

3. Theory: analytical model development

Others have developed models for predicting the resistance force on a capsule in the bowel [22,24–26,29], and they all rely on