Evaluating the Resistant Force of a Vibro-Impact Self-Propelled Capsule Moving in the Small Intestine

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Summary. In this work, we study a mathematical model for evaluating the resistant force of a vibro-impact capsule self-propelling in the small intestine with a consideration of its anatomy. Circular fold is the main source of intestinal resistance that needs to be overcome during the endoscopic procedure. Our model is able to calculate the resistance of such folds in different dimensions. Finite element analysis and experimental testing are presented to validate the proposed model. Our investigation shows that the resistance reaches its maximum immediately after the capsule is driven against the fold, and drops off gradually during the crossing motion.

Introduction

Diseases of surface lining of the small intestine are highly challenging to diagnose and treat. To develop new endoscopic devices capable of self-propelling in the small intestine, endoscopic engineers need to take the complex anatomy of the small intestine into account, in particular the circular fold of the small intestine, when evaluating the performance of their designs. The purpose of the present work is to develop a mathematical model for accurately predicting the resistant force of the capsule-type devices moving in the small intestine and use the model to test the vibro-impact self-propelled capsule developed in the Applied Dynamics and Control Lab at the University of Exeter [1, 2].

According to the movement of the small intestine, most of the research works (e.g., [5, 4]) assume that the capsule distends the intestine in the radial direction when assessing the intestinal resistance. However, this assumption is only valid for a very short time interval during the intestinal movement. For most of the time of diagnosis, the capsule is in one-sided contact with the intestinal wall, so the resistance from the hoop pressure does not apply. For this reason, Guo et al. [7, 8] estimated the intestinal resistance for a self-propelled capsule by considering both partial and full capsule-intestine contacts. In the present work, we use the cylindrical capsule as an example and take the circular fold of the small intestine into consideration to study the required driving force for self-propulsion and the capsule's dynamics in clinical scenario.

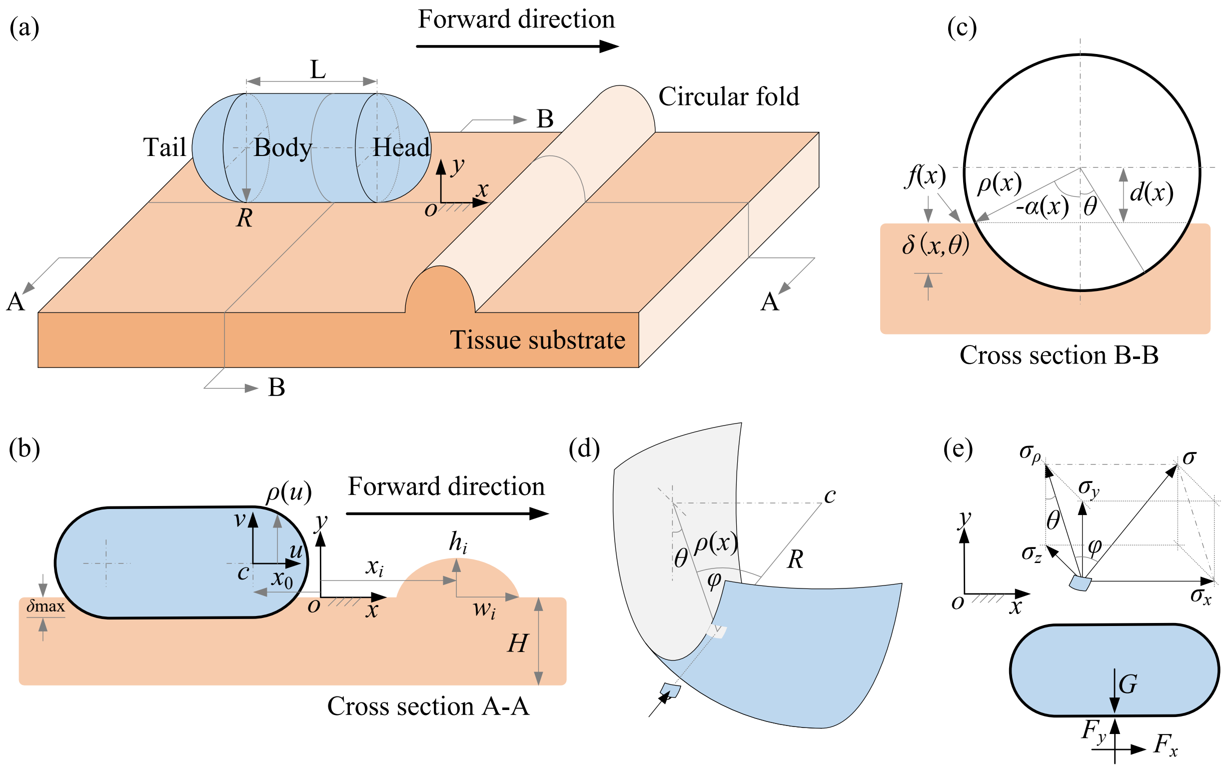

Figure 1: (a) 3D schematic of an endoscopic capsule moving towards a circular fold on a flat tissue substrate. (b) Cross section A-A shows the horizontal and vertical location of the capsule by x_0 and $\delta_{\max}$, and the location, width and height of the ith fold by x_i, w_i and h_i. (c) Cross section B-B shows the capsule-substrate contact angle, $\theta \in [-\alpha(x), \alpha(x)]$. (d) The stress, $\sigma(x, \theta)$, is exerted on the capsule shell as a normal pressure. (e) Integrating the x and y components of the pressure yields the horizontal and vertical reactions, where F_y is balanced by the capsule's gravity, G, and F_x resists the capsule's motion.

Mathematical modelling and validation

The interaction between the capsule and a tissue substrate is schematically illustrated in Fig. 1. As seen, the capsule's hemispheric head and tail is connected by a cylindrical body with a length of L and a radius of R. When the capsule moves horizontally in x-direction, it engages with the circular fold of the small intestine, resulting in complex interactive forces and capsule motion. The detailed modelling procedure can be found in [9].

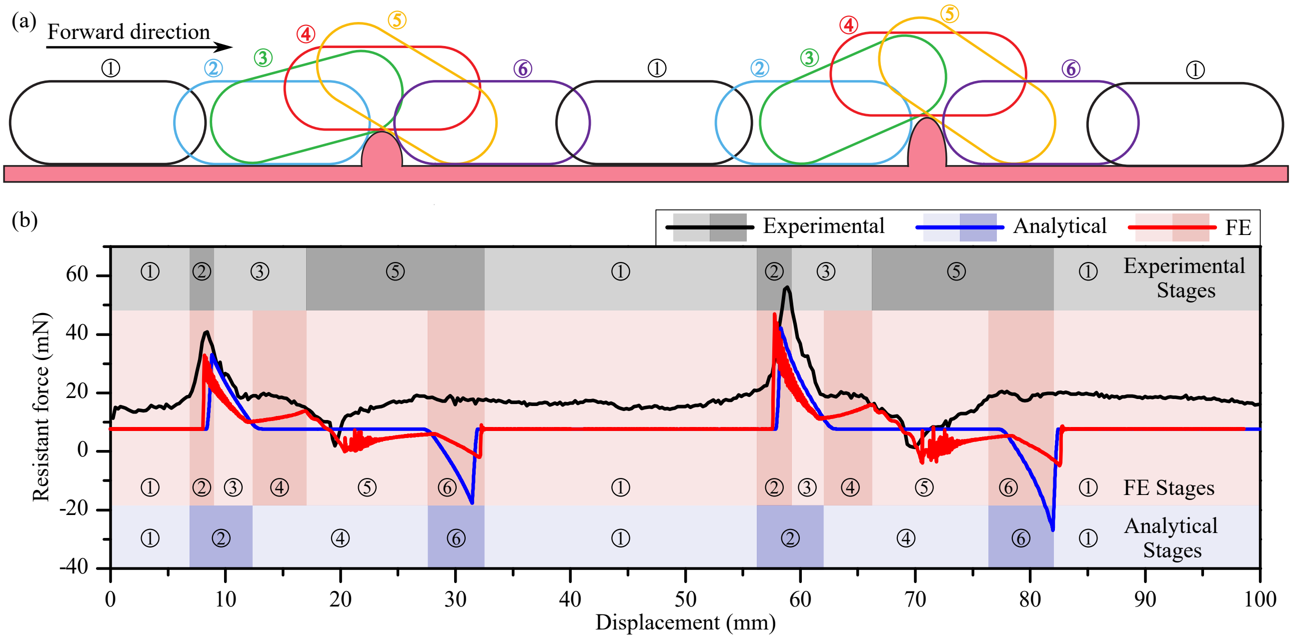

Figure 2: (Colour online) Resistant force acting on the capsule as a function of capsule's displacement when the capsule was pulled on a cut-open synthetic small intestine consisting of two different circular folds in a constant speed of 8 [mm/s] obtained from the mathematical model (blue line), the FE model (red line) and the experiment (black line). FE model can capture all of the six stages of the capsule's motion. Due to the limitations, experiment missed Stages ④ and ⑥, and the mathematical model cannot capture Stages ③ and ⑤. Parameters for the mathematical and FE models were chosen as $E = 100$ [kPa], $G = 33.96$ [mN], $\mu = 0.2293$, $R = 5.50$ [mm], $L = 15$ [mm], $H = 0.69$ [mm], $x_1 = 12.66$ [mm], $h_1 = 1.67$ [mm], $w_1 = 1.665$ [mm], $x_2 = 62.66$ [mm], $h_2 = 2.34$ [mm] and $w_2 = 1.545$ [mm], which were identified from the experimental setup in [8].

In order to validate the analysis, the mathematical and finite element (FE) models adopted the parameters corresponding to the experimental setup described in [8]. Under the same position, the one-to-one correspondence between the capsule's posture and the resistant force is shown in Fig. 2. According to the FE result, the process of capsule's crossing over a circular fold can be divided into six stages. Although some stages were missed by the mathematical model and the experiment due to their limitations, here we are interested with the maximum resistant force experiencing by the capsule when it crosses over the fold.

Conclusions

In conclusion, the FE model captured all of the crossing stages, but the computation was so time-consuming that we only adopted a 2D FE model to sacrifice its accuracy. Nonetheless, all these three (analytical, FE and experimental) methods yielded consistent results for evaluating the maximum resistant force.

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