Dynamics of a vibro-impact self-propelled capsule encountering a bump in the small intestin

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Abstract. Given the anatomy of small-intestine, this paper investigates the kinetic response of a vibro-impact capsule moving through the inner wall of the small intestine, going over single or multiple bumps during its moving, during which the capsule is subjected to resistance from the bumps. In order to make the simulation environment more realistic, two mathematical models of resistance are proposed, simulating a band of annular folds and a cone of cancerous tissue inside the small intestine. Two types of overturning are also designed without considering capsule rotation as well as considering capsule rotation. The resistance analysis of the two kinds of bumps and the two overturning methods has been carried out and found that the conical bump gives less resistance to the capsule under the same conditions, due to the reduced contact surface, while the resistance to the capsule becomes more complex when capsule rotation is taken into account. We will then analyse the kinetic response of the capsule over the bulge under different parameters based on numerical simulations and bifurcation analysis.

Introduction

The main method of examining the inner surface of the small intestine is by using capsule endoscopy, the problem of which is that intermittent peristalsis may lead to a full view of the intestinal surface. Capsule passage times range from 14 to 70 hours [1]. This can be very burdensome for the patient. Prior to the Covid-19 pandemic, endoscopy units in the UK failed to meet demand targets [2]. The average diameter of the adult small bowel is 3.5 cm [3] and therefore the size of the capsule is severely limited. This paper proposes the use of a vibration-driven capsule robot to travel through the small intestine, allowing it to travel over different types of small bowel bulges and then perform kinetic analysis. This will reduce the size of the capsule and speed up the process, while allowing better design parameters to be derived.

Results and discussion

We have completed the derivation of all physical models and equations. Building on previous research, in this paper we will add a conical projection and create a mathematical model of the rotation of the capsule itself. A schematic diagram is shown in Figure 1. In a rotating capsule, the capsule is divided into three parts: head, body and tail. The stress and torque given to it by the intestinal tissues in the vertical direction are integrated separately, and this stress should be balanced with gravity and the torque should be zero, which in the case of the head leads to (1).

$$\begin{cases} F_y = \dfrac{\rho(x)}{\cos\varphi(x)} \displaystyle\int_{x_2+R\sin\gamma}^{x_2+R} \int_{-0.5\pi}^{0.5\pi} \sigma_y(x,\theta)\mathrm{d}\theta\mathrm{d}x + \int_{x_2}^{x_2+R\sin\gamma} \int_{-0.5\pi}^{-\beta} \sigma_y(x,\theta)\mathrm{d}\theta\mathrm{d}x + \int_{x_2}^{x_2+R\sin\gamma} \int_{\beta}^{0.5\pi} \sigma_y(x,\theta)\mathrm{d}\theta\mathrm{d}x = G \\ M = \left(\displaystyle\int_{x_2}^{x_2+R\sin\gamma} \int_{-0.5\pi}^{\beta} \sigma_y + \int_{x_2+R\sin\gamma}^{x_2+R} \int_{-0.5\pi}^{0.5\pi} \sigma_y + \int_{x_2}^{x_2+R\sin\gamma} \int_{\beta}^{0.5\pi} \sigma_y \right)(x-c_x)\dfrac{\rho\mathrm{d}\theta\mathrm{d}x}{\cos\varphi} + \left(\displaystyle\int_{x_2+R\sin\gamma}^{x_2+R} \int_{-0.5\pi}^{0.5\pi} \sigma_x + \int_{x_c}^{x_c+R\sin\gamma} \int_{-0.5\pi}^{-\beta} \sigma_x \right)(p-c_y)\dfrac{\rho\mathrm{d}\theta\mathrm{d}x}{\cos\varphi} = 0 \end{cases} \quad (1)$$

ρ is the radius of the section, σ is the stress applied, γ is the angle of inclination of the capsule, β is the angle associated with γ and x, and the absolute value of p is the distance from the centre of the tail of the capsule to the y-axis. c_x and c_y are the coordinates of the centre of the capsule.

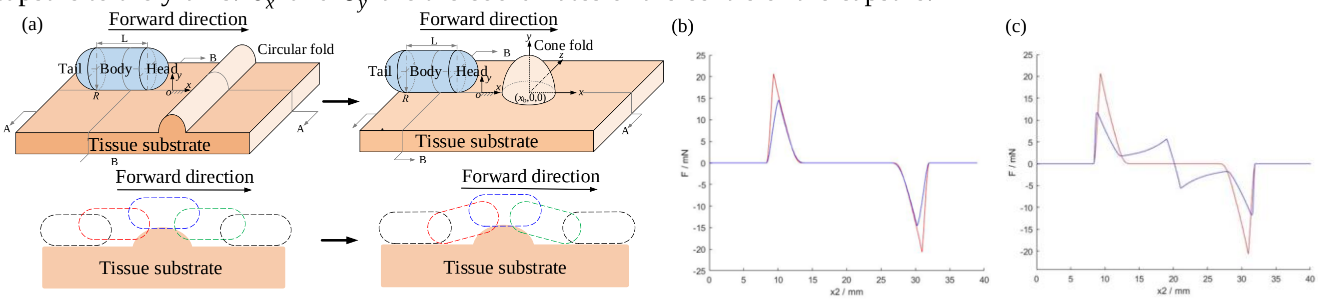

Figure 1: In (a), the capsule will go over two types of bumps, and there are two ways in which the capsule will go over. In (b) the blue line represents a conical projection and the red line represents a ribbon projection. In (c) the blue line represents the rotated way, the red lines represent the non-rotated way.

Solving the equation gives the resistance given to the capsule by the intestinal tissue in the x-direction. The curve of this resistance is shown in Figure 1(b)(c). The next work will investigate the dynamic response of the capsule throughout the process of overturning the bulge based on bifurcation analysis.

References

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