Dynamics of a self-propelled soft capsule moving in the small intestine

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Summary. In this work, we study the dynamics of a vibro-impact soft capsule self-propelling in the small intestine for capsule endoscopy through finite element modelling. Soft coating by using the super-soft silicone rubber was used to reduce the potential damage induced by the rigid capsule on the intestine. Our studies indicate that the dynamics of the capsule becomes complex due to the capsule-intestine interaction, and the coating's elastic modulus and thickness may affect the performance of the capsule significantly. Therefore, a proper selection of these coating parameters is vital for capsule design.

Introduction

The small intestine, an anatomical site previously considered inaccessible to clinicians due to its small diameter and lengthy size, is the part of the gastrointestinal tract between the stomach and the colon as illustrated in Fig. 1(a). Since its introduction into clinical practice twenty years ago, capsule endoscopy [1] has become established as the primary modality for examining the surface lining of the small intestine. However, its reliance on peristalsis for passage through the intestine leads to significant limitations [2], in particular due to the unpredictable and variable locomotion speed. Significant abnormalities, e.g., small-bowel bleeding, may be missed, due to intermittent high transit speeds that lead to incomplete visualisation of the intestinal surface. Furthermore, each case produces up to 100,000 still images, from which video footage is generated, taking 30-90 minutes for the clinician to examine in its entirety. The current procedure is considered both time-consuming and burdensome for clinicians.

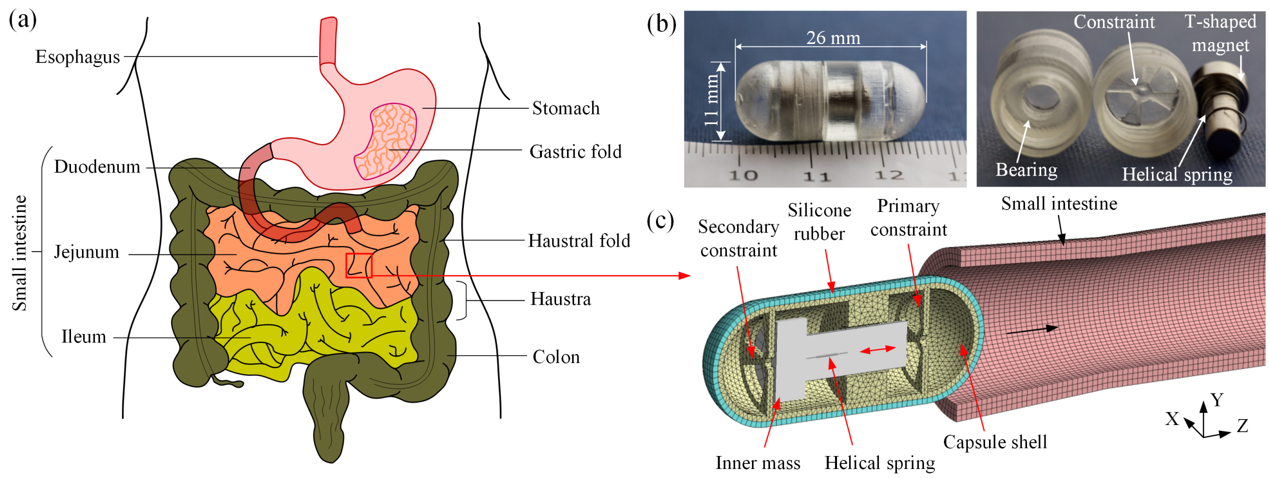

Figure 1: (a) Anatomy of the gastrointestinal tract, (b) external and internal views of the rigid capsule prototype [3] and (c) cross-sectional view of the finite element model, where the coated capsule consists of an inner mass (T-shaped magnet) vibrating and impacting with the primary and the secondary constraints under external magnetic excitation and the interaction of a helical spring.

Building a reliable propulsive mechanism in a capsule (with 26 mm in length and 11 mm diameter) for active endoscopy is a challenging task. Different propulsion methods were proposed in the past few decades for small-intestine diagnosis. The purpose of this work is to study the dynamics of a soft capsule self-propelled in the small intestine through finite element (FE) modelling. The self-propelled capsule developed in the Applied Dynamics and Control Lab at the University of Exeter [3] as shown in Fig. 1(b) can progress either forward or backward driven by its internal vibrations and impacts. Previous FE investigation [4, 5] has focused on studying the capsule-intestine interaction by using a rigid capsule made of polyethylene. However, to reduce the potential damage caused by the rigid shell on the intestine and optimise the capsule's movement, super-soft silicone rubber was used to coat the capsule shell. In this work, we explored the complex dynamics of the coated capsule moving in the lumen of the small intestine as presented in Fig. 1(c) under different coating parameters, such as the coating's elastic modulus and thickness.

Finite element model

FE modelling of the capsule-intestine contact was carried out by using ANSYS WORKBENCH with the consideration of material parameter configuration, geometry, contact settings, meshing, constraints and loads. As can be seen from Fig. 1(c), the polyethylene capsule shell was costed by the super-soft silicone rubber uniformly, and the diameter of the coated capsule was kept as 11 mm. The inner mass made by a T-shaped magnet can move forward and backward under the excitation of an external square-wave magnetic field. The frequency, amplitude and duty cycle ratio of the magnetic field were the control parameters to be tested, and the capsule was driven within a small intestine with an inner diameter of 10 mm. If the interaction force between the inner mass and the capsule is greater than the intestinal friction, the capsule will move either forward or backward. In the present work, we studied the influence of capsule coating's elastic modulus and thickness on its dynamics and progression speed and compare them with the original capsule without any coating.

Numerical results

Capsule's progression and phase trajectories under different elastic moduli of the coating obtained from the FE model are presented in Fig. 2. Based on our simulation, the capsule has an average speed of 14 mm/s when the elastic modulus of the coating is 8 psi, and the average speed is 21 mm/s when the coating is increased to 10 psi. As the elastic modulus increases to 12, 14 and 16 psi, the capsule oscillates at its original position only without any progression. According to our observation, this was due to the fact that the intestine moved together with the capsule, so no relative movement was generated between the capsule and the intestine. When the capsule has no coating, the average speed of the capsule is 18 mm/s. As can be seen from the phase portraits in Fig. 2, the capsule has periodic motions for all the cases. However, the capsule cannot repeat the exact periodic motion, which is due to the asymmetric capsule-intestine interaction.

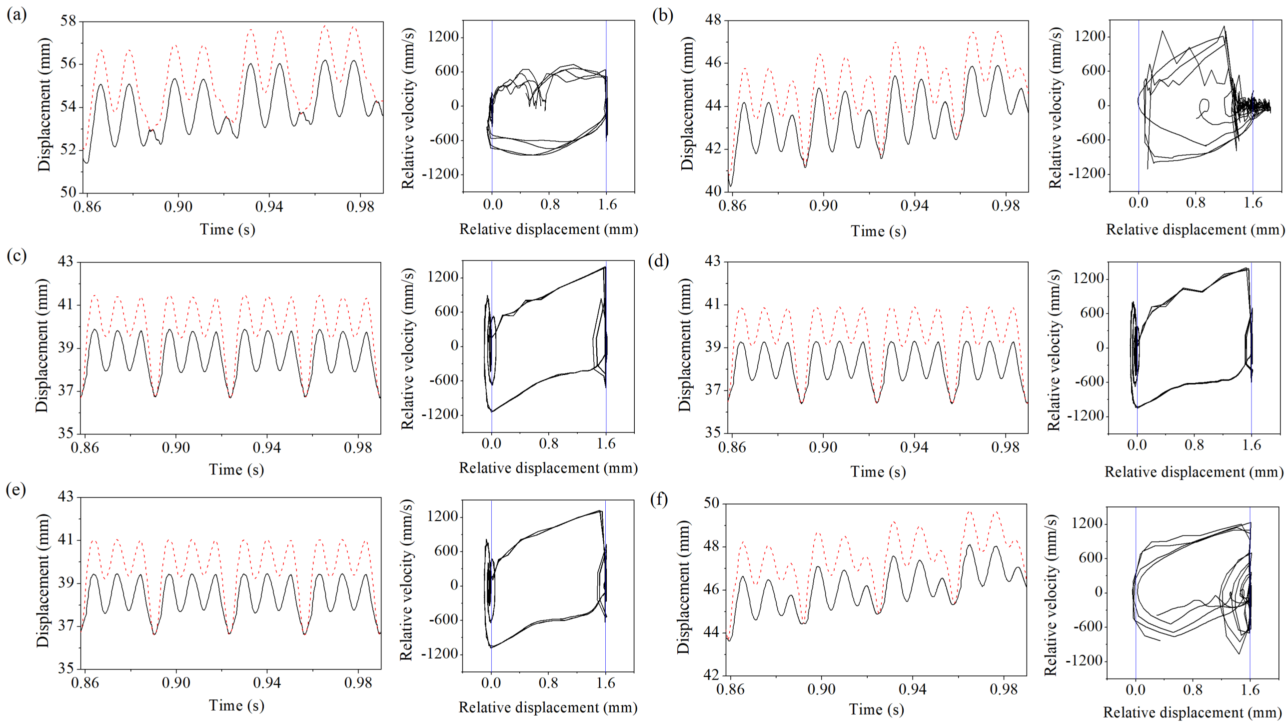

Figure 2: Time histories of displacements of the capsule (black solid lines) and the inner mass (red dashed lines) and their corresponding phase trajectories (relative displacement versus velocity between the inner mass and the capsule) obtained for the elastic moduli of the coating at (a) 8 psi, (b) 10 psi, (c) 12 psi, (d) 14 psi, (e) 16 psi and (f) no coating. The inner mass was driven by a square-wave excitation with the frequency of 30 Hz, the amplitude of 0.3 N and the duty cycle of 80%. Left and right vertical blue lines on the phase portraits indicate the impact boundaries for the secondary and the primary constraints, respectively.

Conclusions

To conclude, the coating of the capsule has a significant influence on the nonlinear motion of the capsule. With a proper selection of elastic modulus and thickness of the coating, an optimum progression of the capsule can be achieved. Our further studies indicate that a harder coating may lead to a greater capsule-intestine contact pressure, while a thicker coating can reduce the contact pressure which can minimise the damage induced by the capsule on the intestine.

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