Dynamics of a soft capsule robot self-propelling in the small intestine via finite element analysis

Jiyuan Tian*, Zepeng Wang*, Yang Liu* and Shyam Prasad**

**Engineering Department, University of Exeter, North Park Road, Exeter, UK, EX4 4QF*

***Royal Devon University Healthcare NHS Foundation Trust, Barrack Road, Exeter, UK, EX2 5DW*

Abstract. This work aims to study the dynamics of a vibro-impact capsule robot interacting with a small intestine via three-dimensional finite element modelling. The capsule was coated with an ultra-soft elastomer to reduce the potential secondary damage to the intestine by its hard shell. It was found that the softer the elastomer coating is, the less contact pressure between the robot and the intestine is, so leading to less potential traumas. Optimum control parameters, such as excitation frequency and duty cycle ratio, were obtained. The findings will be used for prototype fabrication and control system design for the soft capsule robot.

Introduction

Capsule robot, an effective endoscopy technique to diagnose and treat the interior of the gastrointestinal (GI) tract [1], often interacting with the epithelial lining of the digestive tract, potentially induces secondary trauma due to violent vibration and motion of the capsule hard shell or the capsule's external accessories. The small intestine, as the longest portion of the GI tract, with its small diameter combined with peristalsis and segmentation, is considered the strait stage for controlling the movement of self-propelled capsule robots [1]. Previous finite element (FE) studies [2] had primarily investigated the capsule-intestine interactions under different intestinal anatomies by using a rigid capsule made of polyethylene with constant moving speeds, and then, a two-dimensional (2D) FE model have been developed to study the vibro-impact capsule robot developed in the Applied Dynamics and Control Lab at the University of Exeter [3]. In order to reduce the potential trauma to the intestine caused by the hard shell while optimising its progression efficiency and improving the reliability of the FE model, a super-soft elastomer coating was applied to a vibro-impact capsule robot via 3D FE modelling. Since it is a time-dependent dynamic model and due to its structural symmetry, it was simplified as a quarter symmetric FE model as shown in Figure 1(a). In this work, the elastomer coatings with different elastic moduli and thicknesses were conducted to explore the mechanical responses of the vibrating capsule in the lumen of the small intestine. The control parameters of the robot, including the amplitude, frequency and duty cycle of the square-wave excitation, were varied to further investigate the dynamic effect of the coating on the vibro-impact capsule with different excitations.

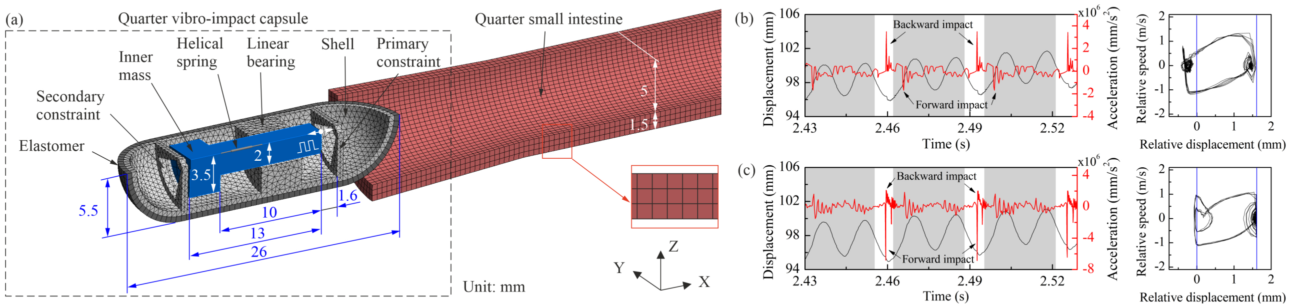

Figure 1: (a) Quarter symmetric view of the FE model, where the coated capsule consists of an inner mass vibrating and impacting with the primary and the secondary constraints under external magnetic excitation and the interaction of a helical spring; FE time histories of inner mass acceleration (red line) and capsule displacement (black line) for (b) the capsule with coating (0.9 mm thickness) and (c) the capsule without coating at the excitation amplitude of 1.2 N, frequency of 30 Hz and duty cycle ratio of 0.8, with their corresponding phase trajectories (right panels), where both vertical blue lines at the relative positions of 0 mm and 1.6 mm on phase portraits represent the secondary (backward) and the primary (forward) constraints of the capsule.

Results and Discussions

Through extensive FE analyses, our proposed FE model can provide quantitative predictions on the contact pressure, resistance force and capsule-intestine dynamics under different elastomer coatings. Figures 1(b) and (c) indicate that soft capsule have fewer forward impact compared with rigid capsule, but with the same capsule moving speed. In addition, it was found that the harder and thinner the elastomer is, the greater the contact pressure between the capsule and intestine, so causing more undesirable tactile sensation to patients.

References

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