Finite Element Modelling of a Vibro-Impact Capsule Moving in the Small Intestine

Jiyuan Tian*, Yang Liu*, Bingyong Guo* and Shyam Prasad**
*College of Engineering, Mathematics and Physical Sciences, University of Exeter, Exeter, UK
**Royal Devon and Exeter NHS Foundation Trust, Barrack Road, Exeter, UK

Abstract. The present work aims to develop a realistic finite element (FE) model to depict the nonlinear dynamics of a vibro-impact capsule moving in the small intestine for capsule endoscopy. The FE model considers both the nonlinear vibro-impact mechanism and the nonlinear viscoelastic deformation of the small intestine with haustral folds. It can provide a realistic prediction of the complex dynamics of the vibro-impact capsule system. In particular, the capsule's dynamics are sensitive to the surface condition of the small intestine, and hence, bifurcation analysis will be conducted to reflect the healthy condition of the small intestine.

Introduction

Since its introduction into clinical practice two decades ago, capsule endoscopy has become established as the primary modality for examining the surface lining of the small intestine, an anatomical site previously considered to be inaccessible to clinicians. As computers have become more powerful, modelling tools based on finite element (FE) methods, e.g. ANSYS Workbench and Fluent, have been employed by researchers to analyse the dynamics of capsule endoscopes in the small intestine. Recent numerical and experimental studies [1, 2] concentrated on investigating the capsule-intestine interaction in terms of contact pressure, intestinal friction and their influence on capsule's propulsion, to develop active and controllable capsule robots for live examinations. However, the studies in [1, 2] assumed that: (i) the capsule's progression speed was constant, and (ii) the intestinal lining was smooth. This work aims to develop a FE model of the vibro-impact capsule system moving in the small intestine with haustral folds, taking into account both the nonlinear vibro-impact mechanism and the capsule-intestine interaction, for the purpose of predicting the complex dynamics of the vibro-impact capsule system in a more realistic intestinal environment.

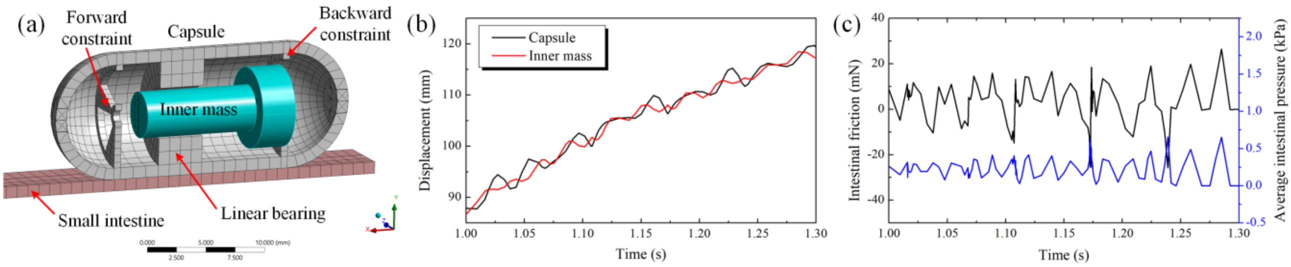

Figure 1: (a) Finite element model of the vibro-impact capsule; (b) Time histories of displacements of the inner mass (red line) and the capsule (black line); (c) Time histories of the intestinal friction (black line) and the average pressure on the intestine (blue line).

Results and discussion

The FE model of the vibro-impact capsule is presented in Figure 1(a), where the capsule was placed on a flat-open small intestine and the inner mass was driven by an external harmonic excitation along its axial direction. The inner mass may collide with either the forward or the backward constraint leading the entire capsule to move rectilinearly. The capsule, the inner mass, and the small intestine were set as polyethylene, structural steel, and viscoelastic materials in the model, respectively, and their mechanical properties were measured by experiments [1]. The total weight of the capsule and the inner mass was 3.47 g. The friction coefficient between the capsule and the small intestine was configured as 0.2293. A sinusoidal force with a frequency of 30 Hz and a magnitude of 150 mN was applied to excite the inner mass. The FE modelling results in Figure 1(b) shows that the overall progression of the capsule was forward but in a forward-backward manner. As the viscoelastic deformation of the small intestine was considered, the response of the capsule was quasi-periodic. The peak displacement of the capsule in each period was larger than that of the inner mass, so the impact action on the forward constraint had an enhancing effect on the progression of the capsule. In addition, Figure 1(c) shows that the friction acting on the small intestine oscillated between ±20 mN. By comparing with the displacement of the capsule in Figure 1(b), the intestinal friction force increased in the positive direction when the capsule moved forward, and vice versa. Furthermore, the capsule-intestine contact pressure fluctuated with the locomotion of the capsule averaging around 0.25 kPa.

References

[1] Guo B., Liu Y. and Prasad S. (2019) Modelling of capsule-intestine contact for a self-propelled capsule robot via experimental and numerical investigation, *Nonlinear Dyn.*, **98**:3155-3167.
[2] Guo B., Ley E., Tian J., Zhang J., Liu Y. and Prasad S. (2020) Experimental and numerical studies of intestinal frictions for propulsive force optimisation of a vibro-impact capsule system, *Nonlinear Dyn.*, **101**:65-83.