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Study on a magnetic spiral-type wireless capsule endoscope controlled by rotational external permanent magnet

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ABSTRACT

In this paper, the authors propose rotating an external permanent magnet (EPM) to manipulate the synchronous rotation of a magnetic spiral-type wireless capsule endoscope (WCE), and the synchronous rotation of the WCE is converted to its translational motion in intestinal tract. In order to preliminarily verify the feasibility of this method, a handheld actuator (HA) controlled by micro controller unit, a magnetic spiral-type WCE and a bracket were fabricated, theoretical analysis and simulations about the control distance of this method were performed, and in *ex-vivo* tests were examined in porcine small intestine to verify the control distance and control performances of this method. It was demonstrated that this method showed good performances in controlling the translational motion of the magnetic spiral-type WCE, and this method has great potential to be used in clinical application.

1. Introduction

Nowadays, wireless capsule endoscope (WCE) has shown its great advantages in detecting the diseases in gastrointestinal tract especially for small intestine due to WCE can provide safe, comfortable, minimally invasive, and complete inspection for gastrointestinal tract, compared with conventional endoscopes [1,2].

However, the significant lack of the current WCEs lies in that they move passively by visceral peristalsis and gravity, which results in lesions in gastrointestinal tract might be easily undetected for the WCEs' one-way movement to anus, and it is hard for physician to observe and diagnose the suspected lesions more thoroughly, repeatedly, and actively. In addition, the future drug delivery, biopsy, and minimally invasive surgery might not be achieved by using the current passive WCEs. Therefore, it is a significant and extremely urgent goal to realize the active control of WCE, in other words, by certain methods the physician can control the speed, direction, and orientation of WCE's motion.

To date, many researches have been devoted to developing various active control methods of WCE.

Mosse et al. proposed using electrical stimulation to propel an endoscope by stimulating muscular contraction [3]. This method realized the forward and backward locomotion for WCE in gastrointestinal tract and the electrodes placed on both ends of the WCE could be used to stop and reverse the WCE within the small intestine, however, the damage to intestine wall caused by electrical stimulation is uncertain although none untoward effect on peristalsis was ever reported, and the wired connection of electrodes is needed in this method leads to it is unrealistic to be applied in real clinical application.

Many researchers focus on the developing of biomimetic robots. Kim et al. developed an earthworm-like micro robot using shape memory alloy actuator to be applied in active WCE [4]. The micro robot can move freely under various environments and be fabricated easily. However, this kind of shape memory alloy actuator needs to be heated and cooled frequently, once applied in real clinical application the actuator's cooling speed will be very low due to the closed environment of gastrointestinal tract. Thus, the robot will propel at a pretty low speed. In addition, the dimensions of the robot should be shortened to a suitable scale so that active WCE can be realized by using such a robot. Kim et al. proposed a paddling based microrobot [5]. This microrobot can move stably inside the lumen and the mean velocity is 17 cm/min over 40 cm length inside the colon of a living pig without any

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serious complications. The main limitation of the microrobot is that it is driven by wired power supply and the dimensions (diameter: 15 mm, length: 43 mm) is a bit big for the use in human gastrointestinal tract.

Compared with electrical stimulation and biomimetic robots, magnetic control shows its great advantage in providing wireless control to WCE without any power supply. Although many wireless power supply systems have been developed and some achievements have been achieved, it is still a big technical challenge for active WCE [6–8]. Magnetic control methods seem to have great potential to be applied in the future clinical application.

Many researchers have proposed their schemes of magnetic control. Ishiyama et al. manipulated a capsule-shaped magnetic actuator by using rotational magnetic field generated by Helmholz coils [9,10]. The actuator consists of a capsule dummy, a permanent magnet inside the capsule and a spiral structure. And the actuator with 1 mm height spiral could move at 5 mm/s and rotate by applying the external rotational magnetic field. However, the whole experimental setup is complex and expensive. And the damage to human body, caused by the electromagnetic radiation from the Helmholz coils, is uncertain. In addition, the control region of this method is very limited for the capsule can only be well manipulated along the axis of the Helmholz coils. Swain et al. manipulated a WCE (including internal magnets) with a handheld external permanent magnet (EPM) in the esophagus and stomach of humans [11]. Under the magnetic control, it is easy to make the WCE move, rotate or stand in the esophagus and stomach. The main limitation of this method is that it is only used in esophagus and stomach environment rather than in small intestine, but the biggest advantage of WCE is to inspect small intestine. Mingyuan et al. investigated design, modeling, simulation, and control issues related to a self-propelled endoscopic capsule navigated inside the human body through external magnetic fields [12,13]. However, the experiments were conducted mainly in ethylene pipe and the experimental setup is also complex. Carpi et al. used a navigation system (Niobe, Stereotaxis, Inc, USA) to achieve robotic steering of a magnetic shell-coating WCE [14]. A couple of permanent magnets can rotate freely so as to generate controlled magnetic field causing the movements of WCE which is placed between the permanent magnets. The WCE can be freely moved with omnidirectional steering accuracy of 1°. The limitation of the navigation system is that it is complex and expensive, and it uses frequently taken fluoroscopic image to localize the WCE, which will do harm to human body in real clinical application. In addition, because the magnetic WCE is placed between the couple of permanent magnets, it will easily crash into one side of the couple of permanent magnets due to the asymmetric magnetic forces they provide to the magnetic WCE, resulting in harmful injuries to small intestine.

In summary, rotational magnetic field can control the magnetic spiral-type WCE's rotation which can be converted to the WCE's translational motion. And this method is better than dragging the magnetic WCE by using a couple of permanent magnets, for the less damage to small intestine would be generated by this method.

Here, in order to avoid the limitations of rotational magnetic field generated by Helmholz coils we propose a new magnetic control method with higher cost performance and simpler equipment and operation, in which an EPM rotated by step motor generates rotational magnetic field to control the synchronous rotation of a magnetic spiral-type WCE which is coated with a magnetic shell (magnetized in radial direction).

In this paper, in order to preliminarily evaluate the feasibility and performances of the new method, a handheld actuator (HA) controlled by micro controller unit and a bracket were fabricated. Control distance of this method was theoretically analyzed and simulated. And in *ex-vivo* tests were carried out in porcine small intestine to determine the control distance and the performances of this magnetic control method.

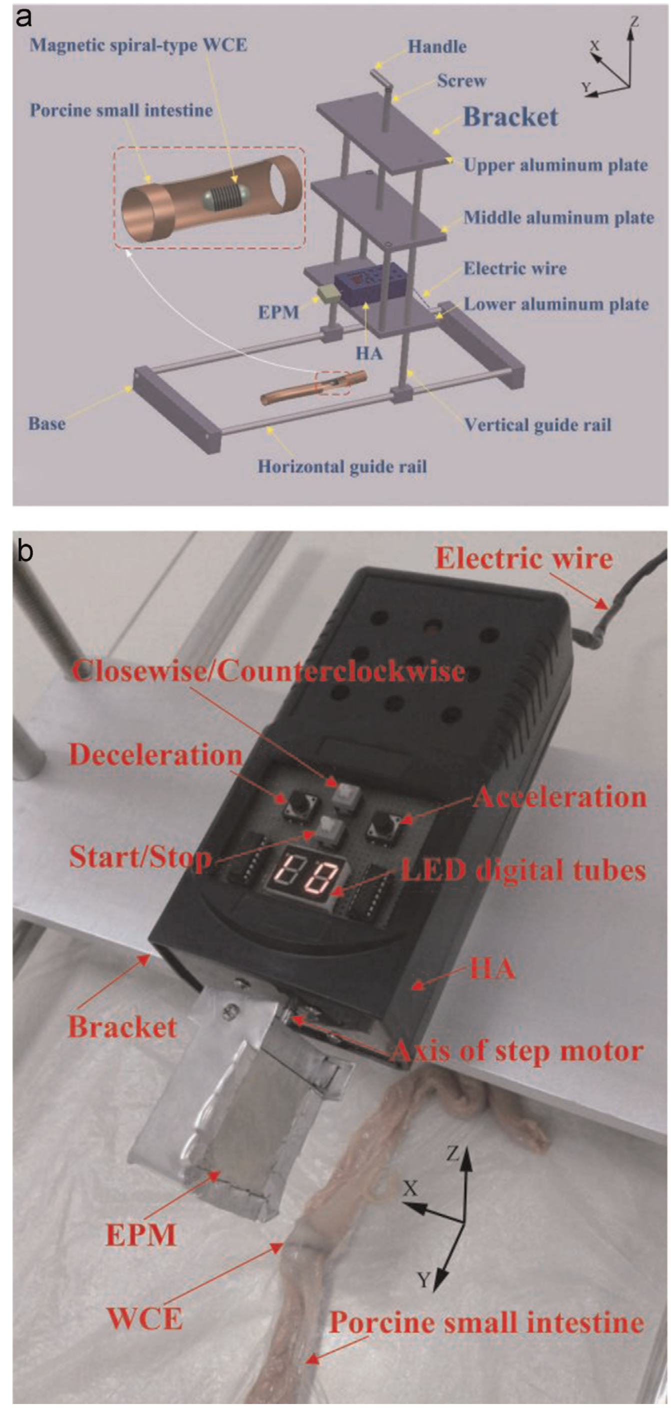

Fig. 1. (a) Overview of the whole experimental setup. (b) Close-up of the EPM's control to the magnetic spiral-type WCE.

2. Structure and operation principle

Fig. 1(a) shows the schematic diagram of this magnetic control method. The whole experimental setup mainly includes HA, magnetic spiral-type WCE, a section of porcine small intestine, and a bracket. Fig. 1(b) shows the EPM's control to the magnetic spiral-type WCE in porcine small intestine. Fig. 2 shows the schematic diagram that the magnetic spiral-type WCE (coated with a magnetic shell) rotates synchronously with the EPM controlled by HA