A REVIEW OF LOCOMOTION SYSTEMS FOR CAPSULE ENDOSCOPY

Lejie Liu, Shahrzad Towfighian, and Amine Hila

Methodological Review

***Abstract*—Wireless capsule endoscopy for gastrointestinal (GI) tract is a modern technology that has the potential to replace conventional endoscopy techniques. Capsule endoscopy is a pill-shaped device embedded with a camera, a coin battery and a data transfer. Without a locomotion system, this capsule endoscopy can only passively travel inside the GI tract via natural peristalsis, thus causing several disadvantages such as inability to control and stop, and risk of capsule retention. Therefore, a locomotion system needs to be added to optimize the current capsule endoscopy. This review summarizes the state-of-the-art locomotion methods along with the desired locomotion features such as size, speed, power and temperature and compares properties of different methods. In addition, properties and motility mechanisms of the GI tract are described. The main purpose of this review is to understand the features of GI tract and diverse locomotion methods in order to create a future capsule endoscopy compatible with GI tract properties.**

I. INTRODUCTION

CONVENTIONAL (flexible) endoscopy has been widely used to identify and monitor diseases in gastrointestinal (GI) tract such as crohn's disease, celiac disease, small-intestine tumors, colorectal cancer etc [1]–[4]. However, flexible endoscopy can have complications and may cause severe pain to patients. In addition, it is hard to monitor some area of GI tract including the largest part of the small bowel [5]. Furthermore, conventional endoscopes need to be operated by professional endoscopists which require a long training time [6]. Therefore, wireless capsule endoscopy was invented, but its functionality is still under investigation. Inchoate capsule endoscopy is basically a pill-shaped device embedding a camera with several LEDs, a coin battery and a data transfer. Once the patient swallows the capsular device, it moves passively through the GI tract via peristalsis. Meanwhile, it starts to take photographs with a constant frequency and transfers the pictures to an external data receiver. The first wireless capsule endoscopy was invented 14 years ago by Swain and Given Imaging (Yoqneam, Israel) [7]. This device consists of several components: an optical dome, a lens holder, a short focal length lens, four LEDs, a complementary metal oxide semiconductor image sensor, two silver oxide batteries, an ASIC radio-frequency transmitter, and external receiving antenna [8].

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Several commercial capsule endoscopies developed by different companies became available after 2000 : EndoCapsule (Olympus, Japan) [9], MiRo capsule (IntroMedic, Korea) [10], and OMOM capsule (Jinshan Science and Technology, China) [11]. In the meantime, second-generation capsule endoscopy named CCE-2 (colon capsule endoscopy) was manufactured and commercially applied in Europe [12]. Compared to the first-generation capsule, the CCE-2 capsule has two cameras with wider view angle, which can provide 172 degrees per camera to observe the panorama of the colon wall. When the frame rate is properly adjusted, the CCE-2 capsular device can last for at least 10 hours.

Although the passive capsule endoscopy technology is in the mature stages of development, many inevitable drawbacks limit its application. For example, it cannot stop at a certain position for diagnostic purposes, and it may cause capsule retention (where a capsule stays in the GI tract for at least 2 weeks) and other complications [13]. Therefore, adding a locomotion system would optimize current capsule endoscopy capabilities.

Several research groups have made great efforts to develop different active capsule endoscopies [14]–[19]. However, because of the complexity of the GI tract and power consumption limitation, automatic capsule endoscopy is still constrained at laboratory level. Therefore, understanding the mechanical properties of the GI tract combined with consideration of requirements of active capsule endoscopy are necessary prerequisites to build a practical robotic capsule endoscopy.

The rest of the paper is organized as follows. Section 2 will discuss the properties and motility of the GI tract and illustrate how these properties affect capsule endoscopy. Section 3 presents the diverse active capsule endoscopies with analysis and assessment. It will end with a view of the next generation capsule endoscopy.

II. GASTROINTESTINAL TRACT PROPERTIES

A. *Fundamental Knowledge*

The gastrointestinal tract includes four organs: esophagus, stomach, small intestine, and colon (Fig. 1). The esophagus is about 25-30 cm in length and 2-3 cm in diameter. The width of the stomach is 25 cm and the volume is 0.1-4 liters to accommodate food [20]. The major areas that the capsule

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endoscopy moves along are the small intestine and the large intestine.

The small intestine consists of three structural parts: duodenum (20-25 cm$\times\phi$3-4 cm), jejunum (2.4 m$\times\phi$2-3 cm) and ileum (2-4 m$\times\phi$1.5-2.5 cm) as shown in Fig. 1.

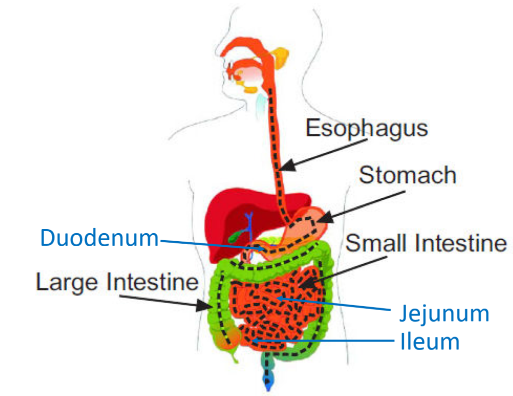

Fig. 1: Components of gastrointestinal tract (Reprinted with permission. Copyright 2011, IEEE [21])

The duodenum and jejunum play major parts in digestion and absorption. The ileum is known as indigested and unabsorbed region [22]. The inner structure of the small intestine is the most complex, when compared with the other components of the GI tract. The plicate surface (mucosal folds) of the intraluminal wall is covered with a layer of villi lying on the lamina propria [23]. This typical viscoelastic tissue is known as mucosa (Fig. 2), which continually secretes a lubricating mucus layer for protection purpose. According to Valdastri *et al.* [24], the thickness of the mucus layer is around 2 mm. Beneath the mucosa (and submucosa) is the smooth muscle layer that can be divided into circular muscle layer and longitudinal muscle layer, as shown in Fig. 2.

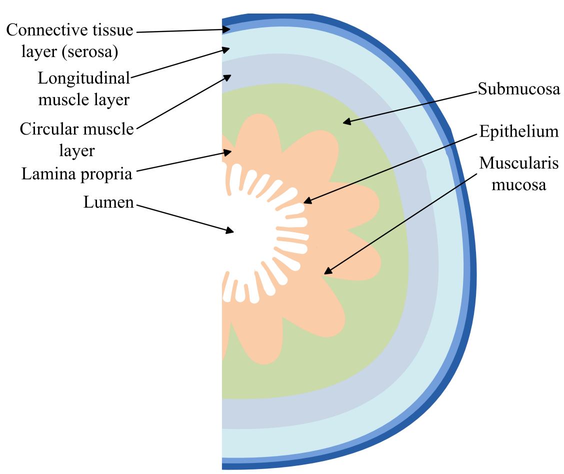

Fig. 2: Layers of the GI tract (Adapted from [23])

In general, the functions of the smooth muscle distributed in the entire GI tract can be divided into two types, phasic and tonic. The phasic muscle dominates the short period contractions commonly engendered in the stomach, small and large intestine, whereas the tonic muscle controls long period contractions that can last minutes or hours generally occurring in the ileocecal sphincter and internal anal sphincter [23]. The small intestine digests and propels food based on the smooth muscle, and consists two basic motions: segmentation and peristaltic.

Segmentation is defined as alternate contractions of different rings of circular muscle as shown in Fig. 3, which is used in the small intestine to divide the chyme into small particles. Particles then are mixed with digestive juices for better absorption. The estimation frequency of segmentation is about 12/min at the distal of duodenum and 8/min in the ileum [25], [26]. The frequency of segmentation varies greatly during different periods. It may be very slow in fasting, and becomes frequent after feeding. Several studies and observations prove that segmental contractions move chyme slowly in the aboral direction [27].

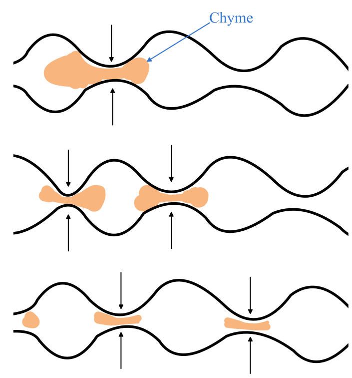

Fig. 3: Segmentation motion of GI tract (Adapted from [23])

Unlike segmentation, peristalsis is known as the sequential contraction and relaxation of contiguous rings of smooth muscle, as shown in Fig. 4. A wave of peristalsis consist of two basic types. Basic peristalsis waves move only 10 cm along the small intestine before vanishing, whereas "peristaltic rushes" occur occasionally and travel along the entire bowel. The common velocity of peristalsis is about 1-2 cm per minute.

The large intestine is a tube 150 cm in length and 6 cm in diameter, and consists of six structural parts: the caecum, the ascending colon, the transverse colon, the descending colon, the sigmoid colon, and the rectum, as shown in Fig. 5. The inner structure of the large intestine is similar to the small intestine but it has no villi because its main function is not to absorb chyme but to store feces. The motility of the large intestine is similar to the small intestine. The rectum commonly contracts more frequently than the more proximal parts.

In addition to GI tract motility, the resistance and pressure exerted by the intestinal wall are commonly concerned when a capsule endoscopy experiences inside the GI tract (especially within the intestinal area), which will be discussed next.

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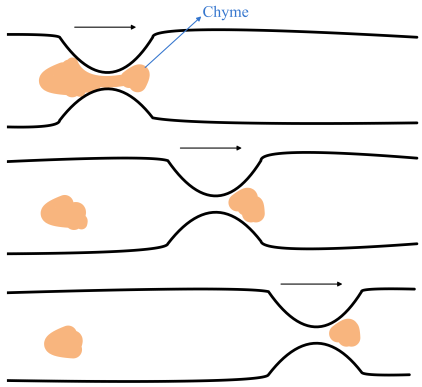

Fig. 4: Peristalsis motion of GI tract (Adapted from [23])

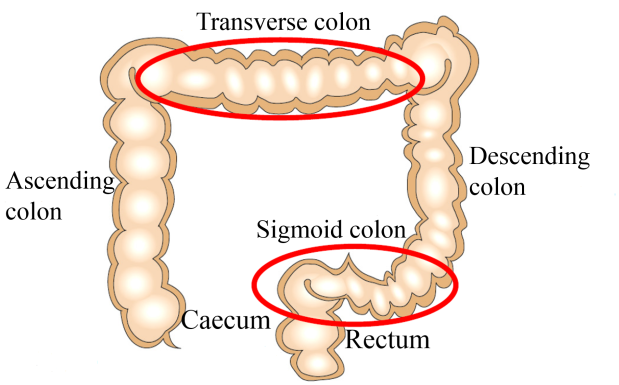

Fig. 5: Components of large intestine (Reprinted with permission. Copyright 2009, IEEE [28])

B. Transit Time and Pressure

For designing a capsule endoscopy, transit time during peristalsis and hoop stress during segmentation are important factors. Fynne *et al*. [29] presented a magnet tracking system to measure the transit time in the stomach and small intestine. The experimental results showed that gastric transit time is about 35.5 min and the small intestinal transit time is 260.5 min. They also reported that peristalsis velocity of the small intestine is 2.2 cm/min during fasting period and 2.3 cm/min in postprandial period, and the gastric contraction frequency is 2.85 ± 0.29/min.

Arman *et al*. [30] reported the hoop pressure measured by a telemetry capsule. However, the in vitro test can only measure the hoop stress caused by small intestine extension (when the diameter of capsule is larger than the diameter of the small intestine). It cannot measure the contracting stress. Based on their study, the hoop stress generated by intestinal extension is about 2.47 KPa. Zhang *et al*. [31] Accomplished an in vivo experiment in the colon using a similar approach. They reported that contraction hoop stress is about 62 KPa during fasting and about 121 KPa after meals. They also found that transit time in colon is about 30 min. Hoop strss is an important design factor for capsule endoscope, since the material should be strong enough to resist the applied stresses.

C. Resistance

Active capsule endoscopy should overcome the resistance acted on it by the luminal wall in order to successfully navigate along the GI tract. Jang *et al*. [32], [33] proposed an experimental study on frictional force and viscoelastic properties of the small intestine. In addition to normal load and friction coefficient, they mentioned that frictional resistance is related to two components: the surface geometry and moving speed. First, a cylindrical shape of the capsule experiences the least resistance, and reducing the contact surface area decreases resistance, but the influence is not significant. Surface geometry effect on frictional proportion was also studied by Wang *et al.* [34]. They pointed out that the diameter of the capsule is more important than the capsule length to affect resistance. Second, higher velocity of the capsule endoscopy generates higher resistance, and it can be explained by considering the stress relaxation property of the body tissue. Therefore, a five-element model as shown in Fig. 6 was built to define the hoop stress acting on the capsule in order to predict the resistance. Furthermore, they established both an analytical solution and a FE model to predict the resistance, which is made of three components: friction force generated by capsular weight, friction force generated by viscoelastic deformation, and the resistance related to the contraction pressure of the intestinal wall [35]. According to their study, the average frictional resistance between capsule and intestinal wall is 20-50 mN under a velocity of 0.5 mm/s.

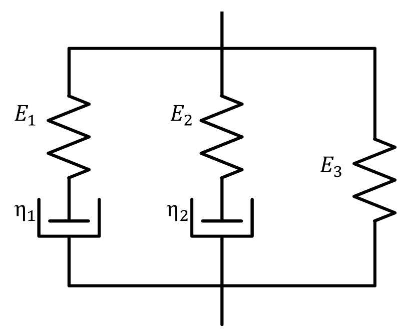

Fig. 6: Five-element model for intestinal tissue (Adapted from [33])

III. LOCOMOTION METHODS

When considering an active capsule endoscopy, the key to propel the capsule is the actuator. Diverse locomotion methods can be roughly classified into three types depending on the use of the actuator: (1) Internal locomotion method, namely, the actuator is embedded on the capsule endoscopy inside the patient's body; (2) External locomotion method, namely, the actuator is outside the patient's body; (3) Other methods which are different from the internal and external methods.

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A. Fundamental Properties of Locomotion System

In order for the locomotion systems to have satisfactory performance, certain properties are desired. First, the speed should be in the range of 15 cm/min to be compatible with GI tract motion and to allow suitable picturing capability. Second, the power requirement should be minimized and when possible an energy support system be offered. Third, the size of the capsule should be no larger than 1.5 cm in diameter and 3 cm in length, otherwise it is uncomfortable for the patient to swallow. Fourth, the temperature of the capsule cannot go beyond 43 °C to be safe in contact with the tissue. Fifth, the locomotion system should make no damage to the body tissues. Current locomotion systems are described next and a summary of each method is given at the end of each category comparing their properties.

B. Internal Locomotion Method

1) Friction Force Based Method: Most researchers prefer the friction force based method, because its simple mechanism leads to a concise structure of the active capsule endoscopy. It can be subdivided into specific mechanisms as follows.

a) Inchworm-like mechanism: The inchworm-like mechanism for capsule endoscopy requires three basic functions: anchoring, elongating, and contracting, done by actuators made of shape memory alloys (SMA). A variety of stopping mechanisms have been applied including the microfibrillar adhesives, proposed by Cheung *et al*. [36], [37]. They adopted beetle inspired micro-patterned adhesives fabricated from polydimethylsiloxane (PDMS) to generate the attraction force, which combines van der Waals forces and liquid adhesive forces, between the capsule and intestine wall. A prototype capsule consisting of SMA wire, compression spring and six legs with adhesive pads on the tips were built as shown in Fig. 7. The capsule can move forward and backward due to the contracting and elongating of the capsule body by sequentially actuating and cooling down the SMA wire.

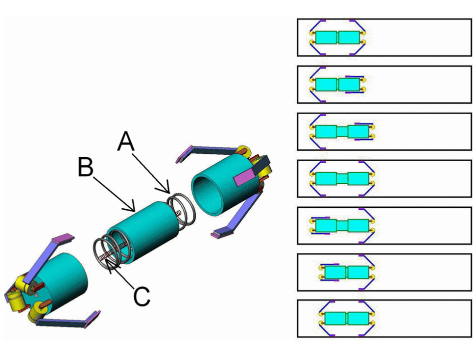

Fig. 7: Locomotion diagram of inchworm-like mechanism (Reprinted with permission. Copyright 2006, IEEE [37])

An inchworm-like endoscopic capsule was also presented by Hosokawa *et al*. [38], [39] applying SMA wire actuator. The mechanism of stretching and contracting the capsule body is practically the same as the above prototype capsule. However, the stopping mechanism is based on suction cups. As shown in Fig. 8a, the suction cup can stick to or remove from the intestine wall by actuating or cooling down the SMA actuator installed in the suction cup. As shown in Fig. 8b, this attachment method can prevent the free segment from slipping in the opposite direction when the capsule moves.

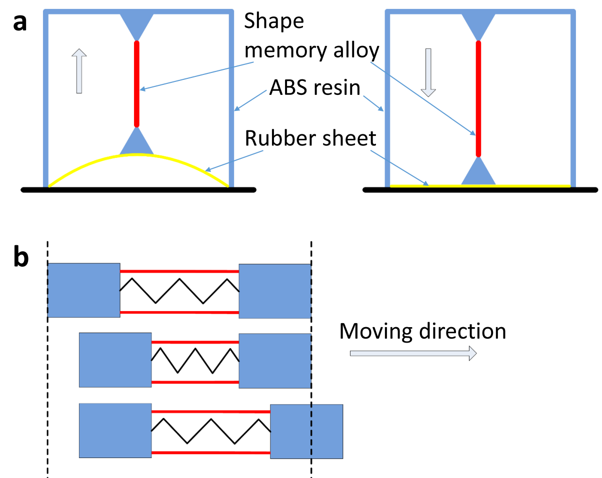

Fig. 8: Locomotion mechanism of suction cup based capsule endoscopy (Adapted from [38]) **a.** suction cup principle, **b.** moving principle

Using SMA wires, another two different inchworm-like capsules were developed by Kim *et al*. [17], [40]–[43]. SMA spring and piezo actuator were used to generate the propelling force, in the meantime, micro-needle and pitch depth of capsule body were applied for clamping purpose respectively. Fig. 9 shows the basic principle of SMA spring combining with the needle clampers. When the SMA spring actuated by electrical heating, the rear segment moves forward whereas the front part stays at the fixed point due to the needle pad. After the SMA spring cools down, the bias spring elongates because of the elastic potential energy to push the front segment forward. The reason the rear and front segments cannot slip along the opposite direction is that all the needles on the pad are assembled facing backward direction so that they can prevent the two segments from slipping backward.

As an alternative actuation method, piezo actuators were also used to move the capsule [42]. The actuators were driven by saw tooth pulse voltage. The outer body of the capsule was covered by several pitch depth for stopping purposes as shown in Fig. 10. The critical stroke is about 7 mm for the earthworm-like robotic capsule endoscopy.

Shape Memory Alloys (SMA): Since shape memory alloys are commonly adopted as actuators for the inchworm-like locomotion systems, it's necessary to understand the constitutive properties and to assess the applicability of SMAs for GI tract use. As its name suggests, shape memory alloys represent a peculiar type of materials which can return to their

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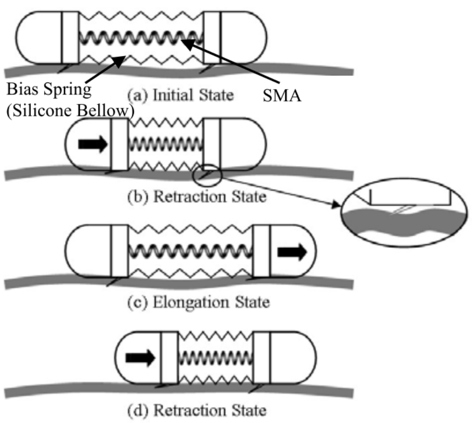

Fig. 9: Moving cycle of needle based mechanism (Reprinted with permission. Copyright 2009, IEEE [40])

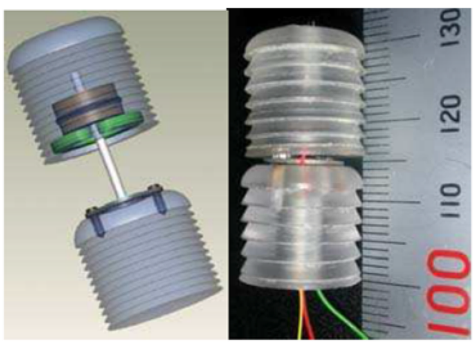

Fig. 10: Piezo actuator and pitch depth stopping mechanism (Reprinted with permission. Copyright 2005, IEEE [42])

original shape after deformation by simply changing the inner or circumambient temperature. The first application of SMAs occurred in 1969 by the Raychem Corporation who produced a Ni-Ti-based hydraulic coupling for the Grumman Corporation [44]. The major property of SMAs is the transformation between austenitic phase and martensitic phase [45]–[48]. As shown in Fig. 11, there are four transition phases: 1) M_S – martensite start (at this temperature, martensite layer starts to appear); 2) M_F – martensite finish (at this temperature, all material specimen completely transform into martensite phase); 3) A_S – austenite start (at this temperature, the austenite layer starts to appear); 4) A_F – austenite finish (at this temperature, all material specimen completely transforms into austenite phase). It's obvious that hysteresis exists between the heating and cooling cycles, and such hysteresis temperature varies due to the change in compositions of SMAs. The hysteresis temperature is about 30 to 50°C for titanium-nickel (TiNi) alloys, around 10 to 25°C for copper-zinc-aluminum (CuZnAl) alloys, and 15 to 20°C for copper-aluminum-nickel (CuAlNi) alloys.

In order to be a practical actuator, an SMA should achieve

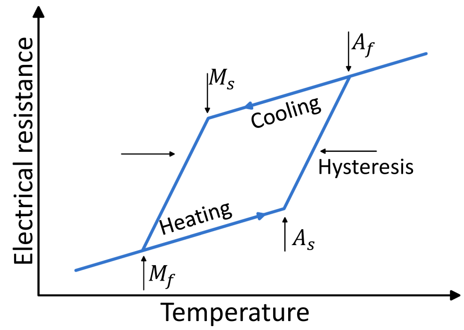

Fig. 11: Four transition phases (Adapted from [49])

the following goals.

- *TWM Effect Requirement:* Common actuators require SMAs to have a two way memory effect (TWM). Usually an SMA presents one-way effect, so a widely used method to obtain TWM ability is to combine the SMA with a bias component such as a bias spring.
- *Enough Cycling Lifetime:* Repeatedly increasing and decreasing temperature may cause material failure, so long cycling lifetime is desired.
- *Appropriate actuator temperature range:* Considering the thermal safety, the heating and cooling transformation temperature should not be higher than 43°C which is the thermal threshold for the GI tract [50], [51].
- *Short hysteresis region:* As mentioned above, each type of SMAs has its own hysteresis region. Minimum hysteresis region is necessary for actuator design. In addition, thermal safety of GI tract is another important reason to shorten the hysteresis region. Therefore, TiNiCu with a hysteresis lower than 3°C and an R-phase transition in TiNi alloys with a 1.5°C hysteresis region are best to be used as locomotion actuators. A summary of inchworm-like based locomotion system is given in Tab. 1.

Summary

According to the table, each inchworm-like capsule endoscopy has its own practical stop mechanism that allows endoscopists for in situ monitoring, and its unique locomotive function can easily accomplish both forth and back motion. However, SMAs based inchworm-like capsule endoscopies have several inevitable limitations: high power consumption in the range of 450-1700 mW and slow response. Moreover, heating SMAs causes conspicuous changes in temperature (12°C in 3 minutes [43]), which may damage the intestinal tissue. In terms of size, SMA and compression spring method [38] has a length 4 cm which exceeds the limit of 3 cm length as the desired length. In addition, the existence of the stoke of SMA springs limits the compactness of capsule endoscopies.

b) Paddle/legged based mechanism: Another prevalent locomotion method of friction force based mechanism is known as paddle based motion. As the name suggests, this type of locomotion mechanism is inspired by paddling a canoe: several paddles or legs embedded on the capsule endoscopy are driven by actuators to push backward against the luminal wall, and the capsule endoscopy can navigate forward due to the reaction force. Park *et al*. [52], [53] proposed a paddling-based capsule endoscopy shown as Fig. 12a.

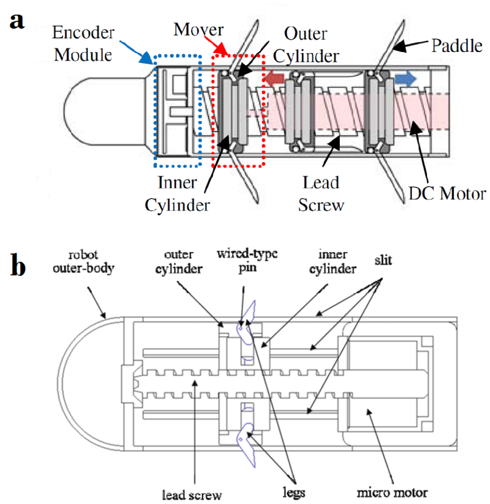

Fig. 12: Paddling-based capsule endoscopy **a.** Park *et al.* (Reprinted with permission. Copyright 2011, IEEE [53]), **b.** Yoon *et al.* (Reprinted with permission. Copyright 2007, IEEE [18])

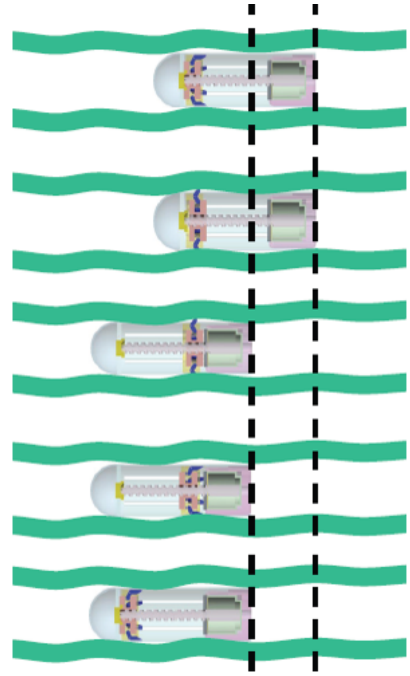

Fig. 13: Principle of moving forward for paddle based capsule (Reprinted with permission. Copyright 2007, IEEE [18])

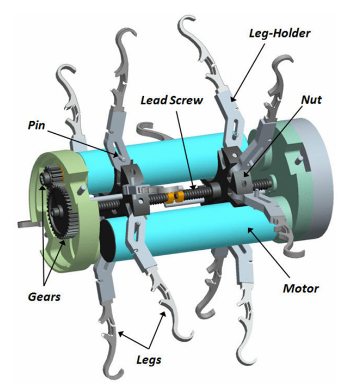

Fig. 14: 12 legged capsule endoscopy (Reprinted with permission. Copyright 2009, IEEE [24])

A similar paddle based capsule endoscopy was presented by Yoon *et al*. [18] as shown in Fig. 12b. A DC motor was selected as the actuator and a lead screw was chosen to transform the rotation movement generated by the DC motor into linear motion. This linear motion could force the paddles to stretch or fold via the outer or inner cylinders (Fig. 13). In order to move forward, the lead screw actuated by the micro motor drives the outer cylinder forcing paddles to stretch, and then paddles clamp the GI tract surface. In the meantime, the lead screw pushes the paddles backward against the wall of GI tract, thus a reaction force drives the outer body to move forward. To return to the initial position, the DC motor reverses, and then the lead screw forces paddles to fold and disconnect from the surface of GI tract. This study indicated that the stroke of the microrobot should be no less than 5.6 mm to advance forward.

A 12-legged capsule endoscopy was also proposed by Quirini *et al*. [24] (Fig. 14). It is driven by a DC brushless motor designed to reduce individual foot forces [54]–[57]. This prototype had two DC motors with corresponding lead screws and nuts. Each motor controls one set of six super-elastic legs. The rear set of legs mainly generates the thrust force,while the front set of legs is in charge of anchoring the capsule when rear legs retract and helps the capsule move forward.

A ciliated cell based capsule endoscopy was proposed by Guo *et al.* [58] (Fig. 15a). The moving mechanism of the capsule is shown in Fig. 15b, where advancement occurs based on the different phases of fore and hind movement of the cilium. In fact, each of the two cilia just acts as a leg controlled by two-way SMA actuator which consists of two parallel SMA springs. The springs are heated and cooled alternatively to move the capsule endoscopy up and forward. A brief extraction and comparison of paddle based locomotion method is organized in Tab. II.

Summary

Comparing Tab. II with the Tab. I, paddle based capsule endoscopies consume almost the same power, but generate significant larger velocities. Velocity reported by the two first methods in Tab. II, have larger velocity than desired velocity of 15 cm/min, which may not allow enough time for picturing folds inside GI tract. Due to the properties of

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TABLE I: Summary of inchworm-like capsule endoscopies

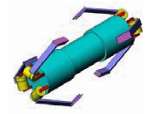
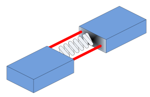
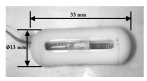
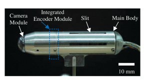
Group	Prototype	Actuator	Size	Velocity	Estimated power consumption(During heating period)
Cheung *et al.* [36]		SMA wire and spring	$\phi10\times22$ mm	40 mm/min	1692 mW
Hosokawa *et al.* [39]		SMA and compression spring	48(L)$\times$16(W) $\times$11(H) mm	9.6 mm/min	450 mW
Kim *et al.* [43]		SMA spring	$\phi13\times33$ mm	Theoretical: 25.5 mm/min Use battery: 10 mm/min	600 mW

TABLE II: Summary of paddle/legged based capsule endoscopies

Group	Prototype	Actuator	Size	Velocity	Estimated power consumption
Park *et al.* [53]		DC motor	$\phi15\times43$ mm	600 mm/min (in vitro test) 170 mm/min (in vivo test)	600 mW (without external loads) 1200 mW (with external loads)
Yoon *et al.* [18]		DC motor	$\phi13\times30$ mm	286 mm/min	Not given
Quirini *et al.* [24]		DC motor	$\phi11\times25$ mm	50 mm/min	430 mW

DC motor and lead screw, paddle based capsule endoscopies cannot navigate backwards along the lumen. Also, this type of capsule cannot stop at a fixed point. Another limitation of this locomotion mechanism is the inevitable risk of tissue damage and capsule retention because of the sharp paddles or legs. Therefore, Quirini et al. [24] have optimized their prototype by adopting a round-shape for the tip of the leg and utilized stronger material for the legs.

c) Crawler mobility mechanism: The last type of friction force based mechanism is called crawler mobility which imitates a car or a tank to advance along the GI tract. Sliker *et al*. [16], [22], [59] first proposed such preliminary capsule endoscopy driven by a DC micromotor. The DC motor leads a planetary gearbox to drive a worm set. The shaft of the gearbox is connected with a stainless steel worm which meshes several worm gears. The protruded worm gears act as wheels to propel the whole capsule endoscopy to navigate forward. Since the first crawler capsular endoscopy is too large to be swallowed by a patient, several subsequent versions have been designed. The final version has six wheels generating a velocity of 600 mm/min. The size is about 35 mm in length and 15 in diameter, and the power consumption is about 200 mW in in-vitro testing. They adopted PDMS as the adhesive tread on the wheels to increase the contact friction traction. Furthermore, they proved that such PDMS tread allowed enough drawbar forces to propel the capsule endoscopy via in-vitro test. Compared with the former two locomotion systems, this locomotion type has faster speed and less power consumption, but its absence of anchoring function and inability of moving backwards are the main drawbacks for clinical operation.

2) Hydrodynamic Force Based Method: Hydrodynamic force based mechanism is widely employed for designing and fabricating swimming robots, therefore, some research groups

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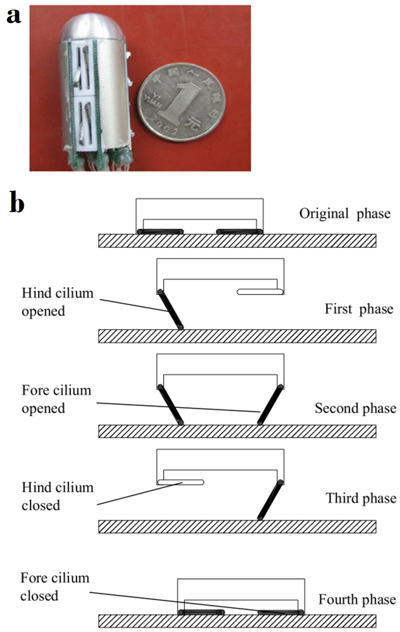


Fig. 15: Ciliated cell based capsule endoscopy (Reprinted with permission. Copyright 2006, IEEE [58]) **a.** ciliated cell based capsule endoscope, **b.** advance gait

adopted this simple mechanism for active capsule endoscopy. Chen *et al*. [60] made efforts for a swimming robotic capsule endoscopy composed of a spiral body and a steering head as shown in Fig. 16. The motility of this prototype capsule endoscopy can be divided into two modes: straight movement mode and steering mode. A DC motor was selected as the actuator for the straight motility. When the motor spins, the spiral body is forced to rotate simultaneously. When the spiral outer surface pushes mucus backward with reaction force, the capsule moves forward. In order to move backward, the DC motor is reversed.

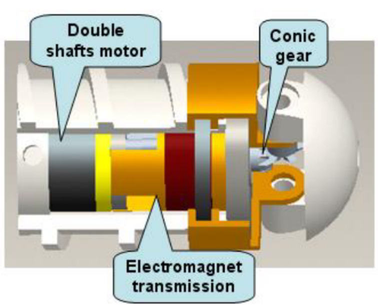
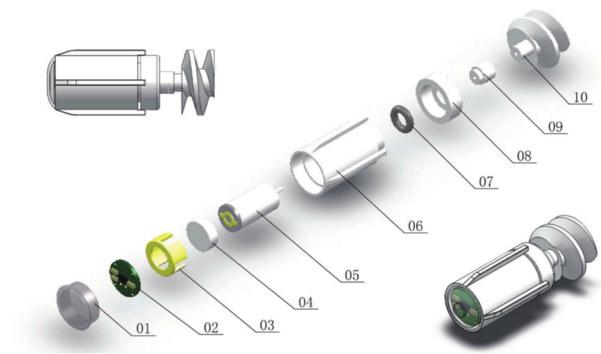


Fig. 16: Swimming robotic capsule endoscopy (Reprinted with permission. Copyright 2009, IEEE [60])

A locomotion system that combines hydrodynamic force and friction force was introduced by Liang *et al*. [15]. As shown in Fig. 17, a DC motor as the actuator drives a screw impeller to rotate, just as the mucus within GI tract pushing against the capsule to move forward based on the hydrodynamic force based mechanism. However, they also considered direct contact which includes the contact between capsule and the intestinal wall combining with the chyme. In this case, the screw impeller pushes against the intestinal wall and chyme instead of mucus, and advances linearly due to the friction force (the mixture of food and intestinal wall act as a stationary nut to transform the rotational motion of screw impeller into linear motion). A propeller based capsule endoscopy is also proposed by Tortora *et al.* [61], [62], which navigate within the stomach like a submarine (Fig. 18).



1. Optical dome; 2. Main board; 3. Motor connector; 4. Battery; 5. Motor; 6. Shell; 7. Seal ring; 8. Seal cover; 9. Flexible coupling; 10. Screw impeller.

Fig. 17: Prototype of screw impeller capsule endoscopy (Reprinted with permission. Copyright 2011, IEEE [15])

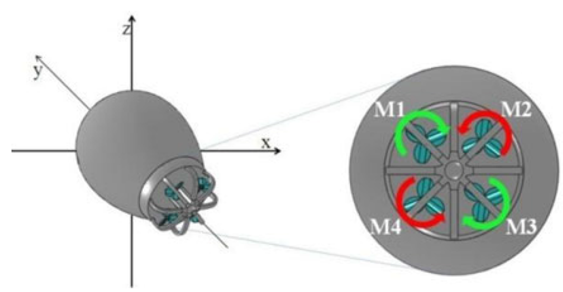


Fig. 18: Diagram of the propeller based capsule endoscopy (Reprinted with permission. Copyright 2013, IEEE [62])

Summary

Comparison of hydrodynamic locomotion systems is presented in the Tab. III; the power consumption of each prototype is as same as the paddle based system because both of them apply the DC motors as their actuators. According to Tab. III, hydrodynamic force based mechanism allows extremely high velocity in both directions. However, because of the spiral shape of the outer body, intraluminal tissue may easily get hurt when the capsule spins with high rotational velocity. High velocity (larger than 15 cm/min) may not allow enough time to picture abnormalities. In addition, like the *paddle based and crawler mobility mechanism, this type of locomotion method cannot stop at a chosen position for clinical purposes.*

3) Vibration Based Method: Vibration based mechanism is another method to drive the capsule endoscopy. An active capsule endoscopy was proposed by Carta *et al.* [63], which is driven by a vibratory motor using multi-coil inductive powering system. As shown in Fig. 19, the vibratory motor is simplified as an eccentric mass m, which rotates around the counter clockwise with a constant radius r and an angular velocity ω. When the vibratory motor starts to spin, the mass m will create a centripetal force which can overcome the gravity and friction force acted on the capsule endoscopy to drive the whole body to navigate forward. This locomotion mechanism requires a minimum value of angular velocity to overcome frictional force. The threshold value of the angular velocity was near 2000 rpm for the specific prototype described above. Considering that vibration based capsule endoscopy exploits the DC motor as its actuator, the power consumption should be similar to paddle based capsule endoscopy. The main strength of this prototype is ease of assembly and simplicity of locomotive mechanism. It is also less invasive than other locomotion methods. However, it is incapable to anchor and sometimes motion instability limits its clinical application.

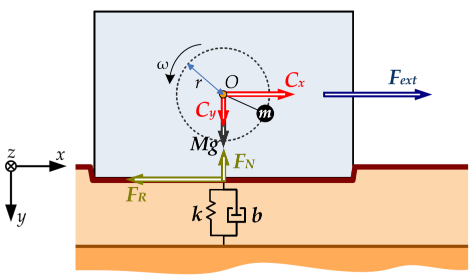


Fig. 19: Vibration based capsule endoscopy (Reprinted with permission. Copyright 2014, IEEE [64])

A vibratory motor has been exploited as a device for the reduction of contacted friction force between the capsule endoscopy and the intraluminal area. Zabulis *et al*. [65] and Ciuti *et al*. [66] presented a capsule endoscopy prototype embedded with an eccentric micro-motor for such purpose. Zabulis *et al*. verified the ability of the vibration based mechanism in friction reduction via several in-vitro tests. Ciuti *et al*. reported a 31% reduction of the friction force along the small intestine tissue and a 18% reduction along the large intestine tissue based on an ex vivo test. The reason why the vibration motility can decrease the friction force is the effect of in-plane vibrations, as described in detail in references [67]–[70].

C. External Locomotion Method

External method generally takes advantage of an external magnetic field (initiated by electromagnetic coils or permanent magnets) to propel the capsule endoscopy. By embedding one or more internal magnets on the capsular body and applying an external magnetic field, endoscopists can manipulate the capsule to accomplish the diagnostic task. Typically, external locomotion mechanisms are subdivided into two specific methods: rotational magnetic field method and magnetic platform method.

1) Rotational Magnetic Field Method: Sendoh *et al*. [71] and Hong *et al*. [72] designed an active capsule endoscopy propelled by external rotational magnetic field respectively. The method designed by Sendoh *et al.* [71] is similar to the hydrodynamic force based method but it concentrates on the external magnetic actuator instead of the micro-motor (Fig. 20). A permanent magnet is embedded on the capsule endoscopy when the magnetic field (initiated by three pairs of coils) starts to rotate. When the capsule body starts to rotate simultaneously due to the magnetism, the spiral structure pushes mucus backwards to drive the capsule endoscopy forward due to reaction force. This capsule endoscopy can change its moving direction by simply changing the rotational plane of the field. The velocity based on an in-vitro test (in tube) is over 1200 mm/min, and the dimension is 40 mm in length and 11 mm in diameter. The strengths and weaknesses are similar to the hydrodynamic force based capsule, but the power consumption inside the capsule is zero for this locomotion method, which avoids heat generation inside the GI tract.

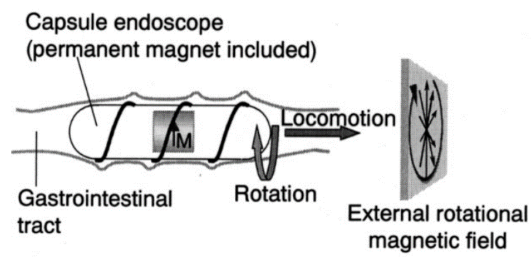
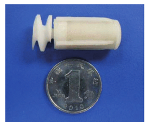
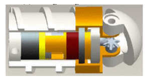


Fig. 20: Diagram of external locomotion method: rotational magnetic field (Reprinted with permission. Copyright 2003, IEEE [71])

2) Magnetic Platform Method: The magnetic platform method is much more mature than other methods because it can be precisely controlled and easily operated. In general, this method requires several external magnets or coils to generate magnetic field changes in multi-DOFs to drive the capsule endoscopy to perform precise motions. The control system basically consists of a human machine interface, a magnetic field controller (a console or robotic arm) with a joystick, and a locating device (MRI or CT machine).

Several research groups have studied this specific method [73]–[79]. Gao *et al*. [73] proposed a magnetic propulsion system that consists of a patient support, a magnet assembly and a magnet support as shown in Fig. 21 . These three components provide four DOFs (moving along the lateral or longitudinal direction and rotating about its vertical or longitudinal axis) for the capsule endoscopy to navigate inside the GI tract. A location control mode that inputs pulse signal

TABLE III: Summary of Hydrodynamic force based capsule endoscopies

Group	Prototype	Actuator	Size	Velocity(in tube)
Liang *et al.* [15]		Micro-motor	$\phi 12\times 29$ mm	3600 mm/min
Chen *et al.* [60]		Micro-motor	Design: $\phi 10\times 40$ mm	600mm/min

is integrated into the human machine interface to guide the capsule to move accurately. The size of this capsule endoscopy is 34 mm in length and 12 mm in diameter without the magnetic shell, and the velocity is about 645 mm/min.

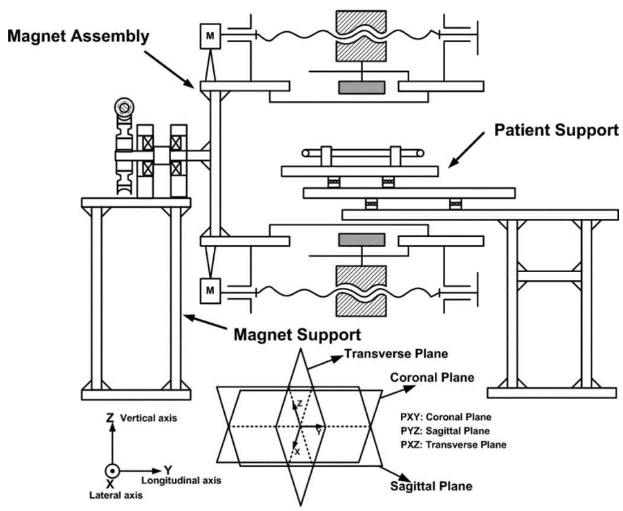


Fig. 21: Diagram of the magnetic propulsion system (Reprinted with permission. Copyright 2010, IEEE [73])

Another magnetic platform based method was presented by CRIM Lab [74]. The control system consists of a human machine interface, a robotic arm and a capsule device. The most important part of this system is the six DOFs industrial robotic arm with a permanent magnet at the tip. By assembling the whole system, they found the optimum working distance between the capsule endoscopy and the external permanent magnet is 150 mm, and the related attraction force is about 315 mN. The diameter of the capsule is 18 mm and the length is 40 mm. The average velocity is about 5 cm/min, which is slower than desired velocity of 15 cm/min.

The main drawback of the external magnetic navigation is the strong force applied on the body tissue from the attractive magnetic force. In order to address this issue, Yim *et al.* [75], [76] designed a compliant structure for the outer surface of the capsule endoscopy (Fig. 22). In this way, the capsule endoscopy is less invasive to the stomach and contracts along axial direction due to the magnetic force in order to fulfil several diagnostic purposes, such as drug delivery or biopsy in the future. When it comes to the manipulative method, the control system is composed of a rotating patient bed, a motorized stage combined with an external magnet which is controlled by a joystick, and a human machine interface. A rolling movement is introduced as follows: when the external magnet rotates, the capsule endoscopy starts to rotate simultaneously, in the meantime, one end of the capsule surface keeps anchor on the gastric wall due to the attraction force. Therefore, the capsule can navigate the whole stomach.

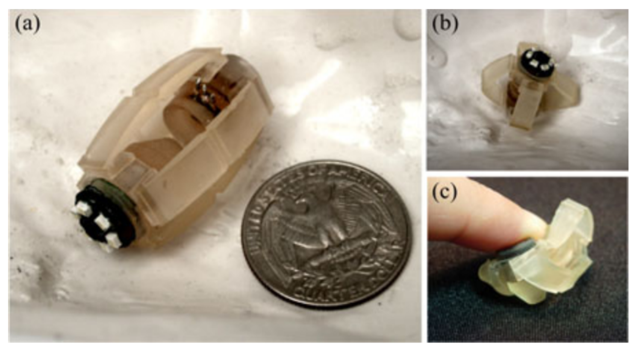


Fig. 22: Soft capsule endoscopy (Reprinted with permission. Copyright 2011, IEEE [75])

Summary

Tab. IV makes a comparison among the different external locomotion methods. The significant strength of the external locomotion method is no or less power consumption for the locomotion system inside the body, therefore the spatial potential due to the absence of battery or power support system, as well as the absence of internal locomotion system, can be utilized for other diagnostic consideration. Another advantage of external method is its precisely controlling and positioning technology. However, the external navigation system is very costly, and tissue damage is a possible complication due to the magnetic attraction.

TABLE IV: Summary of external locomotion capsule endoscopies

Group	Specific method	External actuator	Size	Velocity	Monitor area
Sendoh *et al.* [71]	Rotational magnetic field method	Three pairs of coils	$\phi 11 \times 40$ mm	1200 mm/min	Intestine
Gao *et al.* [73]	Magnetic propulsion system method	Permanent magnets	$\phi 12 \times 34$ mm	645 mm/min	Intestine
CRIM Lab [74]	Robotic arm system method	Permanent magnet	$\phi 18 \times 40$ mm	50 mm/min	Intestine
Yim *et al.* [75]	Rolling locomotion method	Permanent magnet	$\phi 15 \times 40$ mm (original) $\phi 18 \times 30$ mm (contraction)	480 mm/min (linear speed)	Stomach
Lien *et al.* [77]	Hand-held external controller method	Permanent magnet	$\phi 10 \times 22$ mm	20.02-118.25 r/min (rotation speed)	Stomach

D. Other Methods

A hybrid locomotion system for capsule endoscopy was also designed by Simi *et al*. [80] that combined the internal locomotion with external locomotion method. An external magnetic field generated by a permanent magnet is chosen to be the main locomotion function for driving the capsule endoscopy while an additional legged locomotion system is embedded on the capsule to be an assistant locomotion function. When capsule retention occurs, the legged locomotion system is activated to deliver the capsule from the collapsed area.

Another approach to drive the capsule endoscopy is the electrical stimulus method. Yoon *et al*. [81]–[86] designed and fabricated a stimulus capsular endoscopy, which utilized smooth muscles as an actuator. This prototype consists of an embedded electrical stimulation system and an external controller. As shown in Fig. 23, four electrodes controlled by the external controller engender electrical stimuli to lead the contraction of smooth muscle of the gastrointestinal tract. By taking advantage of this contraction, the capsule advances along the opposite direction. The moving direction and the velocity are controlled by the external controller, and the maximum velocity is about 180 mm/min. The length and diameter of this prototype are 30 mm and 12 mm respectively. Drawbacks of this locomotion system include control difficulty and possible body system disorders. The body system disorder could be liver function disturbance due to persistent stimulation of muscular or peristalsis motility perturbation [82].

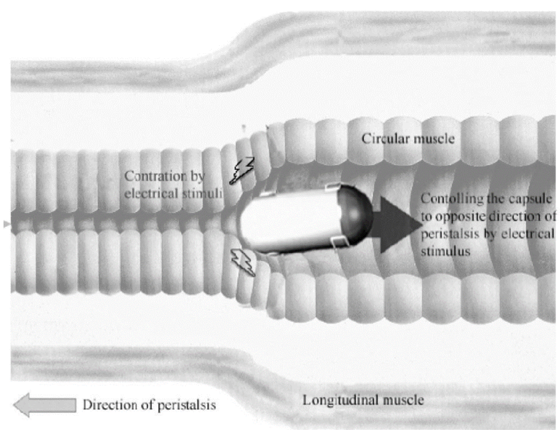


Fig. 23: Electrical stimulus method (Reprinted with permission. Copyright 2005, IEEE [81])

IV. CONCLUSION AND FUTURE CAPSULE ENDOSCOPY

Active locomotion systems for capsule endoscopy are reviewed and categorized along with advantages and disadvantages of each method (Tab. V). Fundamental properties of capsule endoscopes are described and comparisons are made for each locomotion system category. Fig. 24 shows a comparative plot of power consumption and velocity of different categories of locomotion methods. The asterisk, * indicates that the power consumption was not given. The black solid markers mean the locomotion method has the ability to stop for diagnostic purposes, and the empty markers mean it cannot stop. Ability to stop is an important feature for active capsule endoscopes. The desired velocity of 15 cm/min is shown in the figure with a dotted line as a criterion to compare with the speed of different mechanisms. In addition, the power requirement needs to be minimized to be able to use the battery or the energy support system for a longer time. Authors hope this summary can provide a useful overview of current capsule endoscopy locomotion technology and can enlighten researchers to design capsule endoscopies that can overcome current limitations.

An efficient locomotion system should address the following aspects. First, it should consume low power, especially for the internal locomotion method because high power consumption requires additional power support system, and large size. Second, it should apply proper velocity in the range of 15 cm/min because proper velocity guarantees the capsule endoscopy to accomplish the diagnostic purpose (slow velocity causes extra power consumption and wastes time, and high velocity may cause tissue damage). Third, it should have practical ability, such as the abilities of moving forwards, backwards, stopping and real-time control. Finally, it should be safe for GI tract tissue in terms of physical contact and temperature. In addition, future capsule endoscope should be able to to perform therapeutic functions, such as biopsy tissues, unclogging lumen, coagulating, ablating and apposing tissue [87].

TABLE V: Evaluations of locomotion systems

Type of Mechanism	Advantages	Disadvantages
Inchworm-like	Easy moving and stopping mechanism	High power consumption, low velocity, high temperature
Crawler Mobility	High velocity, low power consumption	Inability to reverse and stop
Paddle based	High velocity	Inability to reverse and stop, inevitable risk of tissue damage and capsule retention
Hydrodynamic force based	High velocity in both directions	Inability to stop, inevitable risk of tissue damage, liquid environment limitation
Vibration based	Non-invasive assembly, ease of application	Possible instability, inability to stop
Rotational magnetic field method	High velocity in both directions, no power consumption for the locomotion system inside the capsule, spatial potential	Inability to stop, inevitable risk of tissue damage, liquid environment limitation
Magnetic platform method	No power consumption for the locomotion system inside the capsule, spatial potential, precisely controlling and positioning	High cost of navigation system, bulky equipment, possible risk of tissue damage
Electrical stimulus method	Simplest mechanism, least power consumption	Control difficulty, possible complication of digestive disorder

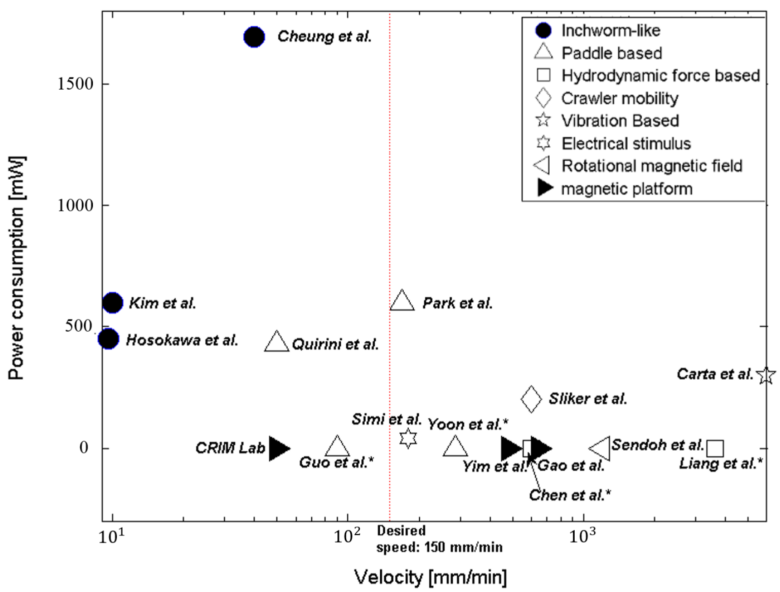


Fig. 24: Comparison of active locomotion systems

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