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A Review of Locomotion Mechanism for Wireless Capsule Endoscopy

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Abstract: Wireless Capsule Endoscopy (WCE) is one of the most influential creations of modern science in biomedical engineering to investigate the entire Gastrointestinal (GI) tract compared to the conventional endoscopy or colonoscopy. It is a swallow-able, non-invasive, painless and patient friendly investigation process of the interior of the human body. WCE is actually a pill shaped device embedded with a camera, a coin like battery and a data transfer. But it takes a long time to travel the total GI tract. Because its locomotion depends only on the peristalsis of the intestine. In order to overcome this core drawback of current commercialized WCE products active locomotion is proposed as a series of strategies used to effectively navigate the device into different organs and conduct therapeutic functions within targeted human tissues. Reviews of several designs in this aspect of research will be discussed in this article.

Keywords: Wireless Capsule Endoscopy (WCE), Gastrointestinal (GI), Endoscopy, Locomotion, Colonoscopy

I. INTRODUCTION

Wireless Capsule Endoscopy (WCE) was first proposed in Nature in 2000 which illustrated a new assistant in the diagnosis of Gastrointestinal (GI) tract diseases including cancers, ulcers, and bleeding [1]-[5]. Traditional wireless capsule endoscopies, which are moved passively by natural peristalsis takes a long time to travel the entire GI tract. But the device featuring active locomotion system are capable of being remote controlled and oriented.

Even though the passive capsule endoscopy technology is in a mature stage of development now, but many unavoidable draw-backs limit its application. This capsule cannot stop at a certain location for diagnostic purposes and it may cause capsule retention and many other complications [6]. 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 [7].

There were many commercial companies developed capsule endoscopies became available after 2000: The first ever wireless capsule endoscopy named M2A was invented before almost 15 years by Swan and Given Imaging (Yoqneam, Israel) [8]. Later on there were many others companies named EndoCapsule (Olympus, Japan) [9], MiRo capsule (IntroMedic, Korea) [10], and OMOM capsule (Jinshan Science and Technology, China) [11]. Meanwhile, 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.

II. TECHNIQUES OF LOCOMOTION

The Commercial endoscopic capsules are passive. They take long time to travel the entire GI tract. Now the concern is active capsule endoscopy, the key to propel the capsule is the actuator. Diverse locomotion methods can be roughly classified into three major 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) Hybrid Locomotion system in which both external and internal system be used.

A. *Ultimate Properties of Locomotion System*

Certain properties are desired in WCE to get satisfactory performance for the locomotion. Firstly, the speed of the capsule should be within the range of 150 mm/min. and to allow suitable picturing capability. Secondly, the requirement power should be minimized and when possible an external energy support system be offered. Thirdly, the

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size of the capsule should be no larger than 1.5 cm in diameter and 3cm in length, otherwise it will be very uncomfortable for the patient to swallow. Fourthly, the temperature of the capsule cannot go beyond 43 C to be safe in contact with the tissue. Fifthly, the locomotion system should make no damage to the body tissues.

B. Internal Locomotion Method

This is the most preferable method to the researchers because of its simple mechanism, which leads to a concise structure of the active capsule endoscopy is the friction force based method. It can be subdivided into specific mechanisms as follows.

1) Paddles based Capsule Endoscopy

This widespread locomotion system of friction forced based method is known as paddle based motion. In this type of locomotion mechanism several paddles are placed on the capsule endoscopy which are driven by different actuators to push backward and forward against the intestinal wall. K. Park et al. [13] proposed a paddling based capsule endoscopy shown in fig. 1.

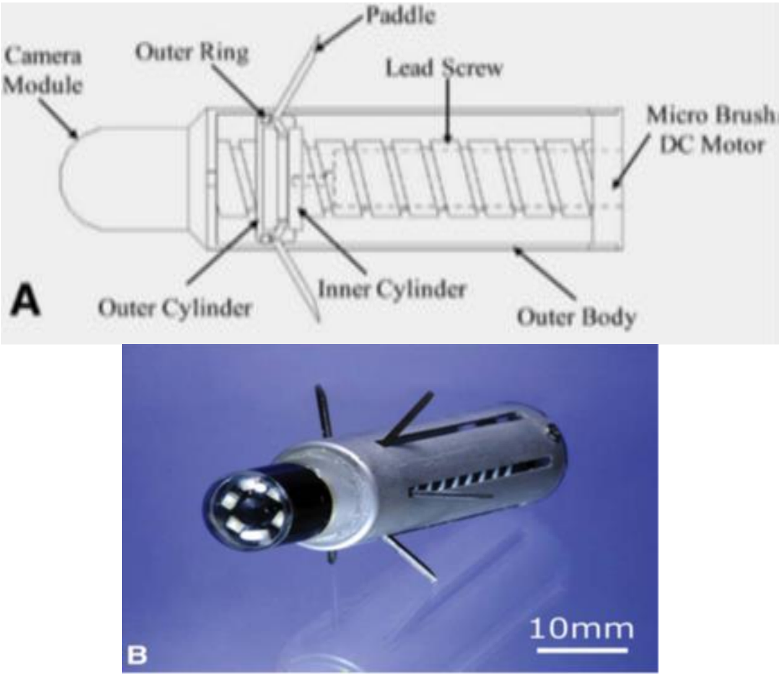


Figure 1: The novel paddling-based locomotive capsule endoscope. (A) the overall structure and major components of the paddling-based locomotive capsule endoscope are illustrated in cross-section. (B) the complete paddling-based locomotive capsule endoscope is shown with fully stretched legs [13].

This modified paddling-based locomotive WCE contains a linear actuating mechanism, based on the combination of a micro brush direct current motor and a lead screw, an inner cylinder, an outer cylinder, an outer ring, 6 long paddles, and also an outer body (Fig. 1). The diameter and length of the locomotive CE are 15 mm and 43 mm respectively and it weighs 14 g. [13].

As the actuator a DC motor was used and a lead screw was handpicked to change the rotational movements generated by the DC motor into linear motion. Here, the paddle could stretch or fold using this linear motion. In order to move forward the lead screw which is run by the micro motor, drives the outer cylinder compelling paddles to stretch. By this time the lead screw pushes the paddles backward against the wall of GI tract. Then a reaction force drives the outer body to move forward. Later on the DC motor reverses to return to the early position.

Limitations: The above mentioned paddle based capsule endoscopy requires high power back up which enhance the size of the capsule and also generates larger velocity which hampers taking clear images of the intestine. This type of capsule cannot stop any desired place and also unable of navigating backward. In addition, it may cause tissue damage of the soft digestive tract during its movements.

E. Yoon et al. [14] also suggested a similar paddle based capsule endoscopy shown in Fig. 3.

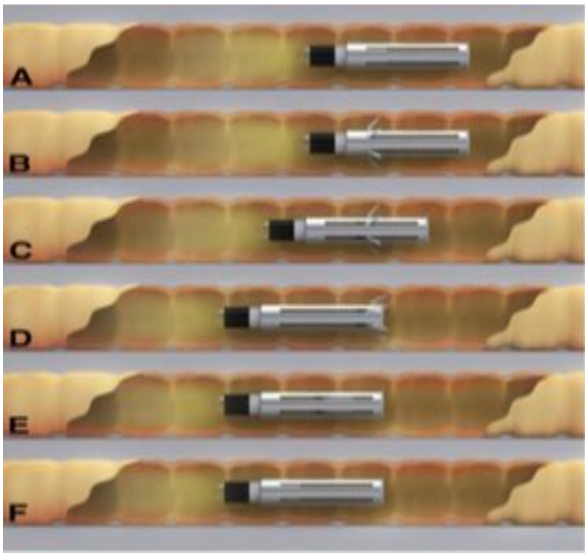
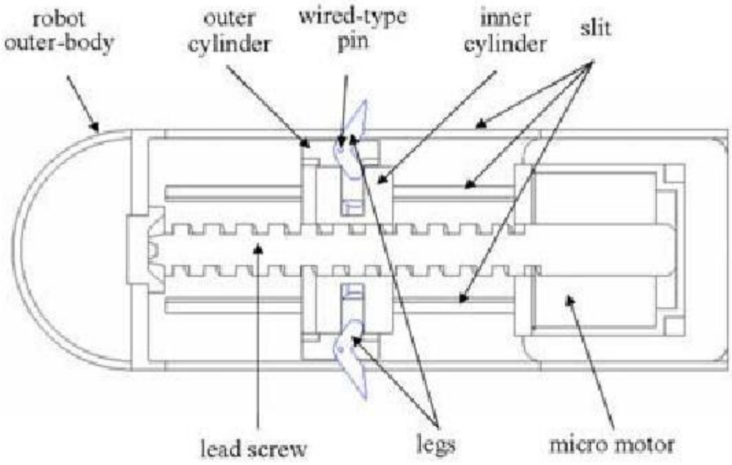


Figure 2: Locomotive mechanism of the paddling-based capsule endoscope. (A) Initial state of the capsule endoscope in the intestine. (B) When the linear actuating mechanism starts to move the inner cylinder backward, the paddles linked to the outer cylinder are stretched, due to the kinematic relationship between the inner and the outer cylinders and clamp the intestinal surfaces. (C) while the actuator moves the inner cylinder farther, the outer body of the capsule endoscope advances forward. (D) End of the stroke of the linear actuating mechanism. At this point, when the actuating mechanism is about to move the inner cylinder forward, the paddles fixed to the intestine are released and folded into the capsule body as the above kinematic relationship works inversely. (E) the cylinders and folded paddles return without the movement of the capsule body. (F) the locomotion principle returns to the same state in step A [13].

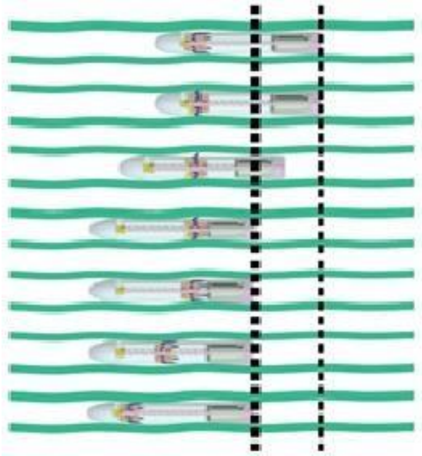
The proposed prototype shown in Fig. 3(a). Consist of a linear actuator. It is actually composed of micro motor, lead screw, an inner cylinder, an outer cylinder, multiple legs and robot outer body. The inner cylinder has some grooves. There is some gap between the grooves and the legs so that the inner cylinder rotates these legs and moves with the legs and the outer cylinder. But the outer cylinder actually connected with the multi-legs with the help of wired-type pin and moves inside of the robot outer body [14].

Finally, in order to reduce the friction force between the robot outer body and the intestinal tract, a semi-sphere head for the WCE is designed and the robot outer body is also layered with lubricant such as silicon oil. The robot outer body has the lateral slits because of the protruding and folding the legs.

Limitations: The drawbacks of this type of method is almost same as the previous paddling based method.



(a)



(b)

Figure 3: (a) concept design of micro robot, (b) Locomotion principle of the proposed capsule-type micro robot [14].

2) 12 Legged Capsule Endoscopy

M. Quirini et al. [15] also proposed a 12 legged capsule endoscopy (fig. 4-5). Actually this prototype uses two DC motors with consistent lead screws and nuts, where each motor control one set of super elastic legs.

Fig. 5 illustrates the internal mechanics of the capsule. Each motor actuates a single set of legs by driving a gear attached to the lead screw. As the screw spins, it translates the nut linearly and a leg holder is fixed to the nut with a pin that rotates it as the nut moves. At the capsule wall there is another pin inserted into a slot in the leg holder. When the nut translates axially up and down along with the lead screw the set of legs makes a progress. All six legs are tightly attached to one nut at a given end of the capsule. Besides all simultaneously open and close as the nut translates.

Limitations: It also requires high power back up and large in terms of size. The capsule may stuck in the digestive tract due to these legs and the legs are very sharp that creates extra spot in the intestine wall.

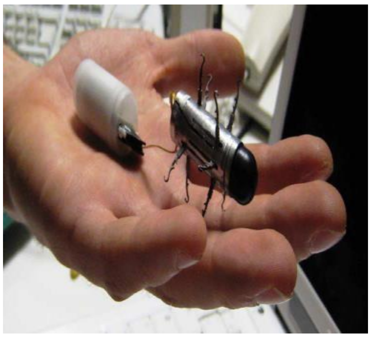


Figure 4: Prototype of 12-legged endoscopic capsular robot. The plastic rear module contains a battery power supply, and will be optimized and miniaturized in future studies [15].

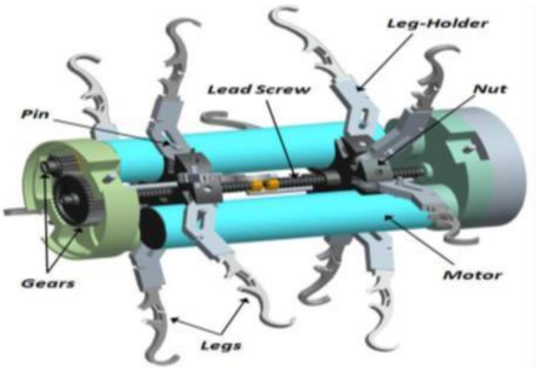


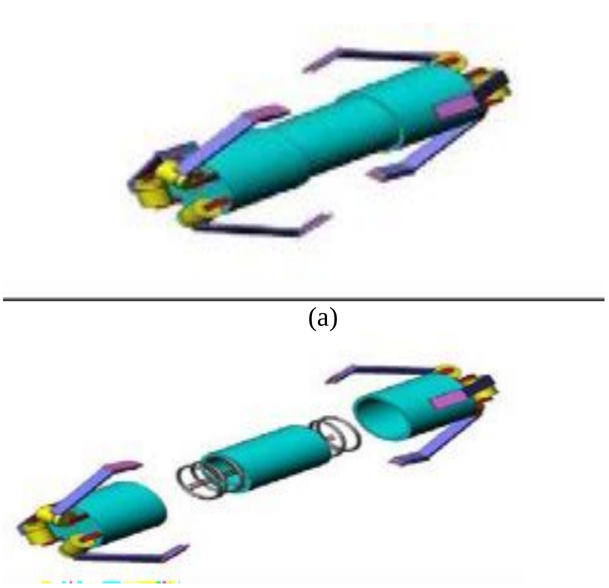
Figure 5: Side view of the capsule with the capsule body hidden to reveal internal components

3) *Inchworm-like mechanism:*

The inchworm-like locomotion system for capsule endoscopy based on anchoring, elongating, and contracting that is performed by the actuators made of shape memory alloys (SMA) and a multiplicity of stopping mechanism have been pragmatic including the microfibrillar adhesives proposed by E. Cheung et al. [17].

In their work they basically implemented beetle motivated micro-patterned adhesive using polydimethylsiloxane (PDMS) in order to generate an attraction force between the capsule and intestine wall. The capsule containing its fundamental properties named SMA wire, compression spring and six legs with adhesive pads as shown in Fig. 6.

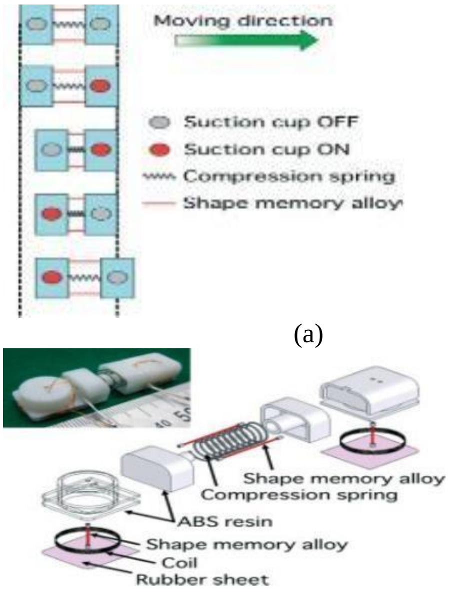
Limitations: This capsule type is also responsible for the tissue damage by it legs and generated heat by its actuator.



(a)

(b)

Figure 6: SolidWorks drawings of the proposed locomotion mechanism, (a) in exploded view, and (b) in the rest (expanded) state [17].



(a)

(b)

Figure 7. Locomotion mechanism of suction cup based capsule, (a) Schematic showing the locomotive mechanism of the prototype crawler, (b) Design and components of the prototype crawler. The picture at top left shows its external shape [18].

Another inchworm like capsule was also proposed by D. Hosokawa et al. [18] (fig. 7) based on SMA wire actuator and the prototype can both elongate and contract longitudinally similar to the above mentioned prototype and adhere to the intestine wall via suction cups. It is actually the combination of two segments joined by a compression spring.

Limitations: The size of this capsule is very large which is almost unswallowable for the patients.

SMA wire based another inchworm like capsule was also proposed by B. Kim et al. [19], [20], [21] that shows the locomotive principle of the proposed micro robot. A silicone bellow acts as a bias spring to provide deformation force. When SMA spring be contracted due to heating the rear body moves forward and the front needles clamp a contact surface. The deformation energy of the silicone bellows elongates SMA spring when it starts cool just after the proper contraction of the SMA spring. Then the contact surface is clamped by the rear needle and the front body moves forward. Finally, the spring force of bellow and SMA spring becomes equal as early equilibrium state. As the step from (a) to (d) in Fig. 8 is repeated, the micro robot can move forward.

Limitations: The SMA spring destroys the compactness of the capsule endoscopy. Moreover, the spring is more longer than the desired length.

Another marginal locomotion method to move the capsule based on piezo actuators [22]. The piezo actuators were also used to move the capsule as a different actuation technique accordingly. Hence, the actuators were driven using saw tooth pulse voltage and for the stopping purposes the capsules outer body was covered by abundant pitch depth as shown in Fig 9

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Limitations: In terms of size this type of capsule endoscopy is also long because the piezo actuators need 100V input that is why a voltage amplifier is required. The response of the capsule is slow.

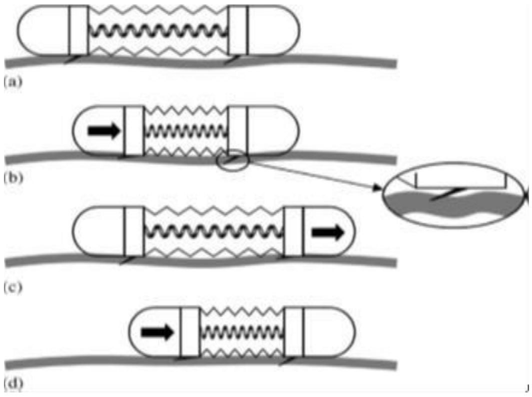

Figure 8: Principle of locomotion. (a) Initial state; (b) retraction state; (c) elongation state; and (d) retraction state [21].

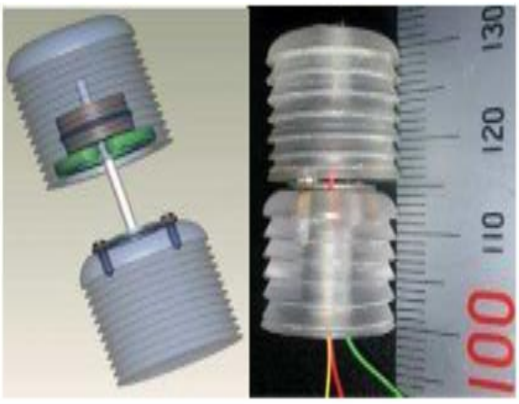

Figure 9: Piezo actuator and pitch depth stopping mechanism [22]

C. *External Locomotion Method*

External locomotion system works using the interactions between inner and outer magnetic fields except using any actuator modules such as internal locomotion system. Actually this prototype has a great benefit in size as well as power consumption, where this system works by embedding one or more internal magnets on the capsular body and using an external magnetic field.

Rotational Magnetic Field Method: M. Sendoh et al. [23] designed an external rotational magnetic field based active locomotion method for capsule endoscopy. This method is almost similar to the hydrodynamic force based method but it mainly focuses on the external magnetic actuator instead of the micro-motor (Fig. 10). In this prototype a permanent magnet is placed where this magnetic field starts to rotate to propel the capsule. As the capsule body starts to rotate concurrently the spiral structure also pushes mucus of the intestine backwards due to the magnetism in order to drive the capsule endoscopy forward due to reaction force.

Limitations: The velocity is very higher than the expected limit and also the size is large. The external locomotion system is very expensive and the magnetic attraction may damage the tissue.

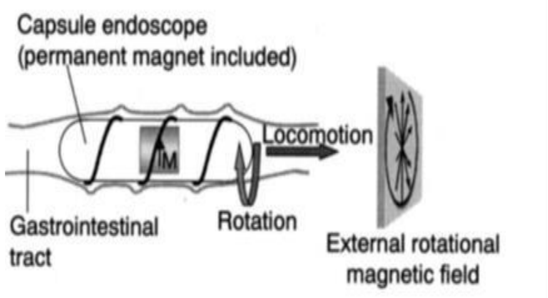

Figure 10: illustration of capsule endoscope-utilized magnetic actuator [23].

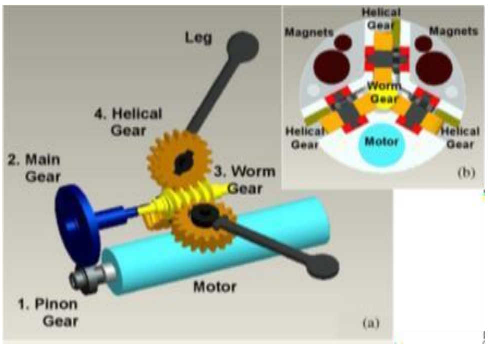

Figure 11: an overview of inner mechanism [24]

D. *Hybrid Locomotion*

Hybrid locomotion is actually defined as a combination of both internal locomotion modules as well as external magnetic navigation. M. Simi et al. [24] proposed a method in which an internal legged mechanism is actuated to help the capsule to overcome some distorted GI tract regions. Integration both locomotion technologies increases the complexity and pretenses which is a big challenge in miniaturization.

The design of M. Simi et al. [24] can be divided into two different aspects of motion, where the on board legged internal mechanism is activated if the capsule is stuck in some collapsed regions inside the digestive tract. In details, the legs can be used together with the external magnetic fields in order to propel the capsule with a level like speed, and also push it out of any regions of collapsed tissue. In addition, the legs can be used to aid in the enlargement of the lumen thus a better view is achieved. This mechanism is illustrated in figure 11. [23].

Limitations: The controlling mechanism is very complicated and may occur the body system disorders due to the Magnetism.

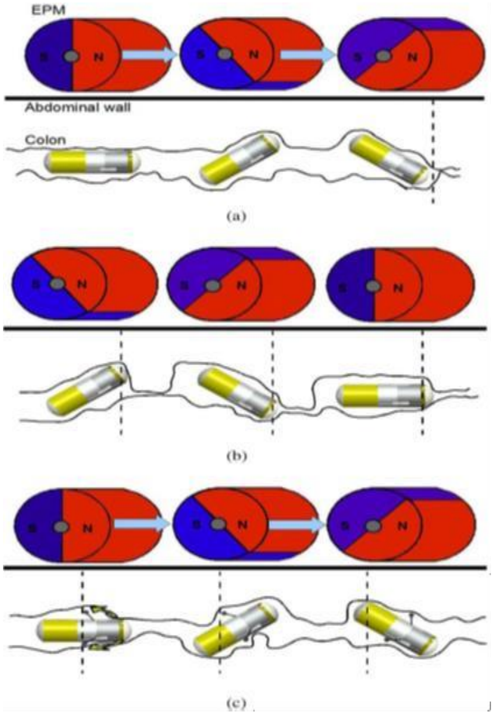

Figure 12: (a) Legs are closed inside the body and the external magnet moves the capsule in lightly collapsed region. Collapsed tissue, corresponding to the dashed line, stops the magnetically driven motion. (b) External magnet only allows capsule orientation, and does not provide net locomotion. (c) Activation of the legged mechanism lifts the tissue and moves the capsule slightly forward. Magnetic locomotion starts again after removing the tissue around the capsule.
The oscillating motion of the external magnet in combination with translation can help to overcome the sharp bends of the intestine [24].

Summary: The paddles or legs based capsule endoscopy provides high velocity whereas it's unable to reverse and stop in a desired place and also unavoidable risk of tissue damage. In the ciliated based prototype also the velocity is high and required power is low, but it also can not reverse and stop. The inchworm based method has a Very easy moving and stopping mechanism, but the consumed power is high and produce huge heat by the SMA actuator that can destroy the tissue and the velocity is not in the satisfied level. The rotational magnetic field based method requires no power for the locomotion and the velocity is high in both directions but its cost is very high and there is a risk of tissue damage. In addition, it's unable to stop the capsule.

Table I: Summary of Different Locomotion Systems

Research group	**Size**	**Actuator**	**Velocity**	**Estimated Consumed Power**
K. Park et al. [13]	15×42 mm	DC motor	600 mm/min	580 mW
E. Yoon et al. [14]	13×30 mm	DC motor	214 mm/min	Not given
M. Quirini et al. [15]	11×25 mm	DC motor	44 mm/min	420 mW
W. Guo et al. [16]	15×35 mm	DC motor	90 mm/min	Not given
E. Cheung et al. [17]	10×22 mm	SMA	40 mm/min	Not given
D. Hosokawa et al. [18]	48×16×11 mm	SMA	9.6 mm/min	420 mW
B. Kim et al.[19-21]	13×33 mm	SMA	24 mm/min	Not given
K. Park et al. [22]	15×41 mm	Piezo Actuator	134 mm/min	Not given
M. Sendoh et al. [23]	11×40 mm	Three pairs of coil	1200 mm/min	Not given
M. Simi et al. [24]	14×44 mm	Magnet for external, DC motor for internal	80 mm/min	100 mW

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III. CONCLUSION

With the progress technology in miniaturization as well as active locomotion, this WCE will play a vital role in GI tract examinations. Even though many investigations remain at the lab level. The coalition of all of these refined enlargements leads to a high degree of expectation for the future. At the same time, from a patient care perspective, the improved capability in conducting therapeutic tasks offers a more comfortable alternative to techniques currently in use. Cost reduction and improvements in small scale fabrication will also contribute greatly to the promotion of the WCE and the techniques will eventually become a regular weapon in handling GI tract disease.

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