Development of Microrobotic Devices for Locomotion in the Human Gastrointestinal Tract

L. Phee\textsuperscript{1}, A. Arena\textsuperscript{1}, S. Gorini\textsuperscript{1}, A. Menciassi\textsuperscript{1}, P. Dario\textsuperscript{1}, Y.K. Jeong\textsuperscript{2}, J.O. Park\textsuperscript{2}

\textsuperscript{1}Scuola Superiore Sant’Anna – MiTech Lab -, Pisa (Italy)
\textsuperscript{2}Intelligent Microsystem Center, KIST, Seoul (Korea)

Abstract

Most gastrointestinal (GI) endoscopy procedures are unpleasant for the patient and are technically demanding for the endoscopist. The authors are developing devices for semi-autonomous or autonomous locomotion in the GI tract. These devices would be introduced into the anus or mouth and will carry a vision system and other endoscopic tools to the area of interest without causing discomfort to the patient.

The prototypes that are discussed in this paper are wired capsule-like devices that propel themselves using the inchworm locomotion principle. In vitro and in vivo experiments were performed with these prototypes and the results will be discussed. This work is the first phase towards the final objective of this project, which is to develop a wireless, swallowable capsule capable of locomotion and inspection of the entire GI tract.

1. Introduction

At present, various types of rigid and flexible endoscopes are used to inspect and to perform therapeutic procedures on different parts of the gastrointestinal (GI) tract. Due to the working characteristics of conventional endoscopes, most GI endoscopy procedures are unpleasant for the patient, are technically difficult for the endoscopist and require long training periods. Furthermore, even with the latest wired endoscopes, a great part of the small intestine still remains unreachable. Studies have shown that most GI ailments can be cured if detected in the early stages which means that mass screening of the population for GI ailments would save lives.

To realize the possibility of mass screening, the authors are developing devices for semi-autonomous or autonomous locomotion in the GI tract. In line with Minimal Invasive Surgery (MIS), these devices will be introduced into the anus or mouth and will function as transportation means to carry a vision system and other endoscopic tools to the area of interest in the GI tract without causing discomfort to the patient.

A swallowable capsule with an embedded micro-camera could perform an effective and reliable diagnosis if it has the ability to detect abnormalities in the entire gastrointestinal tract by inspecting the entire gastrointestinal wall. As demonstrated by the capsule developed by Given Imaging Ltd [1], by relying on normal peristalsis it is possible to obtain clear images just of the small intestine, pylorus and duodenum, which are organs with small lumen and diameters, comparable to that of the capsule. The possibility to stop, go forward and backward, and rotate is of paramount importance to obtain a reliable diagnosis and, in future applications, to perform biopsy and localized therapy (e.g. drug-delivery).

Several locomotion mechanisms for semi-autonomous endoscopes have been developed both by the authors [2-4] and by various researchers [5-7] in the world.

In this paper, the authors illustrate the scientific approach to the problem of “effective” locomotion in the GI tract and the critical analysis of “inchworm” locomotion devices, based on extensor and clamper mechanisms. The practical problems encountered during the development and the testing - \textit{in-vitro} and/or \textit{in-vivo} - of these devices are discussed. Finally, four of the latest prototypes developed by the authors would be presented together with experimental results.

2. The Inchworm Locomotion

The inchworm type locomotion is particularly suited to unstructured or even hostile environments where wheels and tracks fail. An inchworm device would function especially well in a tubular, three-dimensional terrain. With the successes of the pipe inspection robots, researchers decided that self-propelled robotic endoscopes using the same locomotion type could be developed for navigation in the GI tract and other tubular organs. The authors are also in the process of developing inchworm devices catered for locomotion in the GI tract.

An inchworm device is made up of basically two types of actuators: \textit{clamper} and \textit{extensor}. The clamper is used...
to adhere or clamp the device securely onto the “terrain” while the extensor brings about a positive displacement (stroke). The simplest inchworm device consists of two clammers at its ends and one extensor at its mid section. Figure 1 shows the gait sequence in which this device propels itself forward.

![Figure 1. Schematic diagram illustrating the sequence of the inchworm type locomotion concept. The shaded area on the distal and proximal clamping actuators indicates the active clamping states.](image)

The sequence begins with the proximal clamper actuated. With a secure grip on the GI tract, the extensor is activated to propel the distal clamper forward. At this stage, air can be introduced to inflate the GI tract, which is normally collapsed. When the extensor is fully elongated, the distal clamper is activated to grip onto the intestinal wall. The proximal clamper can then be deactivated to release its grip on the GI tract. This is followed by the retraction of the extensor to pull the proximal clamper forward. The cycle then repeats itself. Each cycle results in a net forward displacement, which is the stroke of the inchworm. Primarily, the stroke is the difference in length of the extensor in its elongated and retracted states.

2.1 Efficiency of the Inchworm Locomotion

Theoretically, the inchworm device should advance a distance equal to its stroke length after each cycle of the locomotion sequence. However, this is not true in a real scenario. Losses could result due to factors like slippage, difficult bends and collapsible terrain. As such, we define inchworm locomotion efficiency (\(\eta\)) as the ratio between the real advancement and the theoretical one. The same efficiency can also be expressed as the ratio of real average locomotion speed and the expected one. The inchworm’s locomotion can be broken into 3 distinct features: elongation, retraction and clamping. The individual efficiency of each of these mechanisms contributes to the overall efficiency (\(\eta\)) of the locomotion system. The overall efficiency can be represented by:

\[
\eta = \eta_e \eta_r \eta_c
\]

where \(\eta_e\), \(\eta_r\) and \(\eta_c\) are the efficiencies of the elongation, retraction and clamping mechanisms respectively. Since \(\eta\) is directly proportional to each component, it is important to maintain high individual efficiencies for effective locomotion. It is also critical to fully understand the “terrain” of the locomotive device before an in-depth study of the efficiency can be performed.

In this application, the “terrain” is the human GI tract. It is a fact that no locomotion task can be performed without a qualitative and quantitative knowledge of the relevant features of the surfaces on which the machine will move. This knowledge must be acquired at two distinct and equally important levels. Referring to the inchworm device for GI tract, the first level refers to the mechanical viscoelastic behaviour of the tissues (i.e. displacements of the tissues once a force is applied), while the second refers to the bio-tribological properties of the surfaces, necessary to evaluate the frictional forces which can be exerted to perform locomotion. Then, it is essential to understand the maximum forces which can be exerted without inflicting damage to the tissues. For this aim, it is important to point out the most critical cause of damage and the limitations to the exertable forces. Medical evidence shows that the maximum value of forces is determined at the threshold at which the integrity of the vascular system is disrupted.

The authors have exploited studies on the viscoelastic properties of pig's colon [8] and have also performed tests in order to develop a model of locomotion in the intestine, which is illustrated in a separate work [9]. The results obtained have been used to develop more efficient microrobots for locomotion.

2.2 Previous Experiences

The clamping efficiency is considered the most critical amongst the three defined efficiencies. Like in any locomotion devices, there must exist enough adhesion between the device and the environment for effective locomotion to take place. In previous attempts [2-4], the authors used vacuum to cause the soft GI tissue to be sucked onto the device. However, due to the almost negligible coefficient of friction of the GI tract, insufficient traction forces were derived by simple suction. Moreover, undesirable lesions appear when the vacuum pressure is increased beyond a certain value. However, a notable occurrence is that with the introduction of a vacuum, tubular sections of the GI tract
(colon, small intestine etc) would collapse around any hard object that is in the vicinity of the suction supply. In doing so, the GI tract would take the shape of the hard object, filling any gaps, holes or troughs in the process. To take advantage of this situation, instead of using the vacuum to attain traction forces, it could be used to cause the tissue to fall into the ‘jaws’ of a mechanical clamp (e.g. grippers, pincers, forceps). Having a prominent hold on the tissue, the ‘jaws’ of the clamp can easily close in for a positive grasp. This concept is depicted in Figure 2. The first prototype with this "suction+mechanical" clamping mechanism (or clamer) incorporated at its distal and proximal ends is shown in Figure 3.

**Figure 2.** (Description from the top to the bottom): The clamer is placed into the GI tract with its ‘jaws’ opened; a vacuum is introduced to cause the surrounding tissue to collapse into the ‘jaws’ of the clamp; the jaws of the clamp close to grasp onto the tissue.

**Figure 3.** Prototype with “suction+mechanical” clamping mechanism.

It measures 24 mm in diameter and has lengths of 115 mm and 195 mm when retracted and elongated respectively. A flexible central rubber bellow acts as the extensor which gives the device a stroke of 80 mm when extended. Rubber bellows are used to open and close the clamp jaws while a hole of 2 mm diameter situated in between the jaws is responsible for suction and insufflation of air. Flexible air tubings exit from proximal end of the device to form the ‘tail’ of the inchworm device. These are connected to an external pneumatic distributor. A computer controls the activation of solenoid valves which are responsible for driving the extensor and clammers according to a specified gait sequence.

**Experiments**

*In vivo* experiments were performed on 30 to 35 kg pigs under general anaesthesia. Prior to the experiment, the pigs’ bowels were properly prepared for colonoscopy. Conventional colonoscopy was first performed by a skilled endoscopist to inspect the terrain of the colon. The prototype was introduced manually about 10 cm into the pig’s anus. Upon activation of the gait sequence, the inchworm device propelled itself into the colon with a speed of about 25 cm/min. In the five separate *in vivo* experiments performed, this prototype managed to traverse a distance of 55 to 65 cm from the anus before coming to a halt. It has demonstrated high elongation and clamping efficiencies and the distance traversed is highly repeatable. Its greatest drawback is its low retraction efficiency that ultimately affects the overall locomotion efficiency. In the presence of acute bends, the device begins to stretch and push the tissue and no relative motion occurs between the device and the intestine. This usually happens after the sigmoid colon, at the initial part of the transverse colon. The authors have termed this the *accordion effect* which is illustrated in Figure 4.

**Figure 4.** Illustration of the *accordion effect*.

3. **Capsular Locomotion Devices**

To overcome the problem of the *accordion effect* and to further reduce the dimensions of the device, the authors have developed a series of capsular-like locomotion devices. The inchworm locomotion concept and the “suction+mechanical” clamer are still employed in these devices. However, the disposition of the clamer is different. The devices are configured with at least two
sliding clamps such that one of which would always grasp onto the GI tissue that is distal with respect to the other. In doing so, even if the tissue ‘crumples’ and is thrown into folds during the retraction phase, the device would always clamp onto tissue distal with respect to these folds, resulting in higher retraction efficiency. These clamps are actuated by tendons as they slide along the body of the device, parallel to the direction of locomotion. These prototypes, called EMIL prototypes from the name of the EMIL Project (Endoscopic Microcapsule Locomotion Project – IMC, Seoul, Korea), are shown in Figure 5.

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Table 1 shows the dimensions and characteristics of the three prototypes. It also shows the measured speeds of the devices during in vitro experiments with explanted pig’s intestines laid in a straight path. The locomotion efficiencies can be derived by comparing the measured and the theoretical speeds.

<table>
<thead>
<tr>
<th></th>
<th>EMIL3.1</th>
<th>EMIL3.2</th>
<th>EMIL3.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter (mm)</td>
<td>10</td>
<td>16</td>
<td>20</td>
</tr>
<tr>
<td>Length (mm)</td>
<td>35</td>
<td>35</td>
<td>70</td>
</tr>
<tr>
<td>No. of Clamps</td>
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<td>4</td>
<td>2</td>
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<tr>
<td>Stroke Length (mm)</td>
<td>18</td>
<td>22</td>
<td>40</td>
</tr>
<tr>
<td>Cycle Time (s)</td>
<td>19</td>
<td>28</td>
<td>18</td>
</tr>
<tr>
<td>Theoretical Speed (cm/min)</td>
<td>5.7</td>
<td>9.4</td>
<td>12.0</td>
</tr>
<tr>
<td>Measured Speed (cm/min)</td>
<td>1.3</td>
<td>3.2</td>
<td>4.0</td>
</tr>
<tr>
<td>Locomotion Efficiency</td>
<td>23%</td>
<td>34%</td>
<td>33%</td>
</tr>
</tbody>
</table>

Table 1. Dimensions and characteristics of the EMIL prototypes.

The devices are actuated by external DC motors and a pneumatic distributor as shown in Figure 6. A computer is responsible for the activation of the solenoid pneumatic valves and motors. The operator controls the movement of the devices via a Human Machine Interface (HMI). The devices can be commanded to start, stop and increase or decrease its speed. Other parameters like air pressures and the ability to insufflate air with controlled duration can also be adjusted from the HMI.

Apart from in vitro tests in straight paths (results given in Table 1), extensive tests were also performed to validate the device’s ability to negotiate bends. Pig’s colon (and small intestine) were positioned and constrained in configurations of varying radius of curvature and degree of bend. Artificial humps were also included to replicate the 3D structure of the GI tract. The devices were then introduced at one end and activated. Table 2 shows the
performances of the 3 devices in a typical experimental configuration. In this particular case, the obstacle was a 31 cm long path with a 180° curve of radius of curvature 10 cm. Figure 7 shows the EMIL3.3 prototype navigating this particular bend.

![Figure 7. EMIL3.3 navigating a bend.](image)

<table>
<thead>
<tr>
<th>Time Taken (s)</th>
<th>EMIL3.1</th>
<th>EMIL3.2</th>
<th>EMIL3.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measure Speed (cm/min)</td>
<td>1.3</td>
<td>1.8</td>
<td>2.9</td>
</tr>
<tr>
<td>Theoretical Speed (cm/min)</td>
<td>5.7</td>
<td>9.4</td>
<td>12.0</td>
</tr>
<tr>
<td>Locomotion Efficiency</td>
<td>23.3%</td>
<td>19.0%</td>
<td>24.2%</td>
</tr>
</tbody>
</table>

Table 2. Typical results of an in vitro test in a bend.

Generally, the results show that locomotion efficiencies are slightly lower in bends than in straight paths. The EMIL prototypes can propel themselves in acute bends at low speeds. Comparing to the first prototype (Section 2.2), the EMIL prototypes propelled themselves slower due to their shorter stroke lengths and capsular design. However, they are able to negotiate bends and there reduce the accordion effect, which was the greatest locomotion problem of the first prototype.

System Integration

The conventional GI endoscope has a vision system and light source to capture images from inside the human body. Surgical tools can also be passed through a tool channel for biopsy and other surgical interventions. Thus, a locomotion device for the GI tract would be deemed useless if it does not carry any useful endoscopy tools. To initiate work on systems integration, the authors have incorporated a vision system into the EMIL3.3 prototype. A wired CCD camera with light source measuring 13 mm in diameter and 26 mm in length was integrated into the central portion of the device. As a result, the overall diameter and length of the device were increased respectively as shown in Figure 8.

![Figure 8. EMIL3.3 with camera and light source.](image)

Preliminary in vitro experiments showed the device capable of traversing in a straight path at a speed of about 3cm/min. However, the images captured by the camera were unclear due to illumination and focusing problems. Furthermore, according to medical experts, the dimensions of the device have become too large for it to be tried in animal tests. Although many problems were encountered, valuable lessons were learnt from this first attempt at systems integration. Future work in this area would include the integration of smaller cameras which are more adapted for use in endoscopy. A steerable mechanism would also be incorporated to steer the camera towards the view of interest.

4. Conclusion

Work is in progress to improve the locomotion capabilities of the devices. At the same time, more useful endoscopy tools will be integrated on board the capsule while retaining (and even reducing) its small dimensions. The greatest long-term challenge would be the development of a wireless and swallowable locomotion system for inspection of the entire GI tract. This would mean the integration of a stand-alone power supply to drive microactuators, microsensors and microcontroller on board the device.

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