

Communications

Analysis and Development of Locomotion Devices for the Gastrointestinal Tract

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Abstract—The authors are developing devices for semi-autonomous or autonomous locomotion in the gastrointestinal (GI) tract. In this paper, they illustrate the systematic approach to the problem of “effective” locomotion in the GI tract and the critical analysis of “inchworm” locomotion devices, based on extensor and clasper mechanisms. The fundamentals of locomotion and the practical problems encountered during the development and the testing (*in vitro* and *in vivo*) of these devices are discussed. A mini device capable of propelling itself in the colon and suitable to perform, at least, rectum-sigmoidoscopy (the tract where approximately 60% of all colon cancers are found) is presented. This paper introduces preliminary, but useful, concepts for understanding, modeling and improving the performance of virtually any existing and novel devices for endoscopy of the GI tract.

Index Terms—Colonoscopy, inchworm locomotion.

I. INTRODUCTION

Diseases of the gastrointestinal (GI) tract (stomach and colon cancer, ulcerative colitis, etc.) are common in most countries. According to the National Cancer Institute [1], cancers of the colon are the fourth most commonly diagnosed cancers and rank second among cancer deaths in the United States. However, most colon cancers can be cured if detected at their early stages. There exist several methods to detect ailments of the GI tract without the introduction of intrusive devices into the human body; stool test, double-contrast barium enema and more recently model endoscope systems and genetic analysis just to name a few. However, these will probably never replace conventional GI endoscopy in which diagnosis is based on analysis of real images and biopsy samples. Various academic institutions and industries have embarked on the quest to improve conventional GI endoscopy procedures [2]–[4]. Phee *et al.* [5] presented a thorough survey of these works. More recently, researchers [6] aim to develop autonomous capsules to be swallowed in order to perform diagnosis and even therapy of the gastrointestinal tract. Given Imaging Ltd’s M2A swallowable capsule is capable of obtaining real images of the small intestine for diagnosis of small bowel disorders in humans [7]. In the authors’ laboratory, devices that can propel semi-autonomously or autonomously in some parts of the GI tract [8] are being developed. These devices act as transportation means to carry a vision system to a desired area in the GI tract. Patient comfort and reduced manual handling being top priorities, these devices could promote the possibility of mass screening the population

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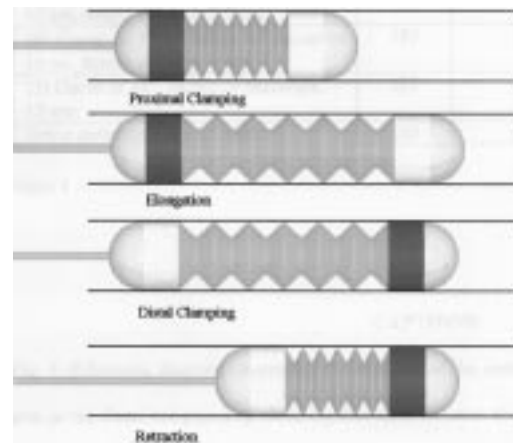


Fig. 1. Schematic diagram illustrating the sequence of the inchworm locomotion principle. The shaded area on the distal and proximal clamping actuators indicates the active clamping states.

for GI ailments. In addition to inspection and diagnosis, future integration of miniaturized endoscopic tools onboard the locomotive devices would allow therapeutic procedures to be performed as well.

In this paper, the authors propose objective and quantitative criteria of efficiency for locomotion in the gastrointestinal tract and to set up “standard” parameters of evaluation to compare different technological solutions. To pursue this aim, the devices for locomotion are analytically evaluated by considering not only the mechanical aspects, but also the interaction model between the devices and the environment (the GI tract in this case) which dramatically affects the behavior and the efficiency of any navigation systems. When the above efficiency criteria have been defined, a technological solution is presented and the results of *in vitro* and *in vivo* tests are discussed and interpreted on the basis of these evaluation parameters and the proposed model.

II. INCHWORM TYPE LOCOMOTION AND EFFICIENCIES

An inchworm device is made up of basically two types of actuators: *clasper* and *extensor*. The clasper is used to adhere or clamp the device securely onto the “terrain” (e.g., the human GI tract) while the extensor brings about a positive displacement (stroke). The simplest inchworm device consists of two claspers at its ends and one extensor at its midsection. Fig. 1 shows the gait sequence of the inchworm device.

Theoretically, the inchworm device should advance a distance equal to its stroke length after each cycle of the locomotive sequence. However, this is not true in a real scenario. Losses could result due to factors like slippage, difficult bends, and collapsible GI tract. As such, the authors define the *inchworm locomotion efficiency* η 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.

In order to optimize the locomotive efficiency, it is important to study quantitatively which factors influence the value of η . The authors propose to break the inchworm’s locomotion into three distinct features: elongation, retraction, and clamping. The individual efficiency of each

of these mechanisms contributes to the overall efficiency η of the locomotion system. The overall locomotion efficiency can be represented by

$$\eta = \eta_e \eta_r \eta_c$$

where η_e , η_r , and η_c are the efficiencies of the elongation, retraction, and clamping mechanisms, respectively. Since η is directly proportional to each component, it is important to maintain high individual efficiencies for effective locomotion. It is also critical to properly describe the mechanical properties of the tissues where the device has to move. To this aim, the authors have carried on dedicated experiments on pig's intestine which separate studies [9], [10] have shown to be similar to the human one in terms of size and biomechanical properties. Since the GI walls are extremely flexible and compliant and their biomechanical and geometrical properties vary significantly from subject to subject, it would be extremely difficult to obtain an accurate expression for the locomotion efficiency. Consequently, the final goal is to formulate a simple expression of the locomotion efficiency to be used as a guide in the practical design of inchworm-based endoscopic devices. The GI tract (colon and small intestines) can be geometrically described as a cylindrical shell having the following typical dimensions.

wall thickness $t = 2$ to 3 mm;
average diameter $\phi = 20$ to 50 mm (when not folded or stretched).

A major issue is to take the mechanical properties of the GI tissue into account in a simple and effective way, starting from the well-known pseudoelastic constitutive equations [11]. First of all, only positive tensions have to be considered since compressive forces would easily collapse the GI tube. Moreover, the strain rate can be considered constant because the elongation of the robot occurs at the constant speed of about 2.5 cm/s. Finally, for small strains ($<5\%$ for the model taken into account) the viscoelastic uniaxial stress-strain relation can be well approximated by the second order relation

$$\sigma = \gamma \varepsilon^2 \quad (1)$$

where σ is the stress and ε is the strain. Due to the nonisotropic nature of the GI tract tissue, the value of coefficient γ varies with the direction of load. In this application, the load is the locomotive force applied in the longitudinal direction, in a direction parallel to the GI tract. For longitudinal strips of tissue, it has been found that $\gamma = 5.0$ MPa \pm 30% (at a strain rate of 0.2 s $^{-1}$) using standard measurement methods [10], [11] applied to pig's colon.

Prior to elongation (with reference to the air insufflation stage of Fig. 1), the extensor is in the retracted state and the proximal clasper is activated and assumed to grip onto the GI tract without slippage. In order for the extensor to elongate, the inchworm device has to overcome an initial impeding force F_c whose intensity comes from the effects of superficial friction and forces required to push open the collapsed lumen in the frontal direction. Due to the existence of friction between the device and the GI tract, part of the compliant intestinal wall would shift together with the advancing distal head at a constant strain rate (0.02 s $^{-1}$). The impeding force increases till a value F_c as the intestinal wall is being stretched. Up till this point, the stroke Δl_0 does not contribute to the effective displacement of the inchworm device. However, beyond this point, slippage would occur as the propulsion force exceeds the impeding forces resulting in F_c becoming constant. The distal head of the device begins to advance forward with respect to the intestinal wall for a distance Δl_1 , which is the effective displacement of the device [Fig. 2(a)].

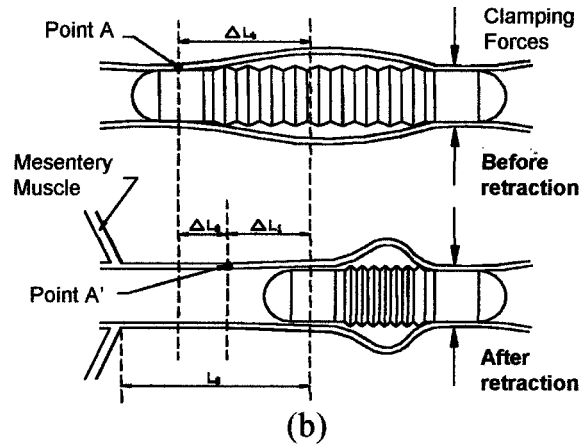
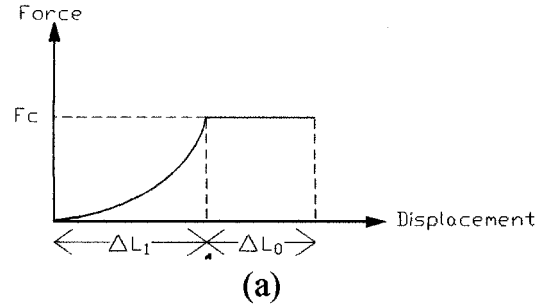


Fig. 2. (a) Relation between force and displacement (b) Losses in retraction efficiency.

The total elongation stroke of the inchworm device is defined as Δl_t . Evidently

$$\Delta l_t = \Delta l_0 + \Delta l_1.$$

Since only Δl_1 contributes to locomotion, we can define the *inchworm elongation efficiency* η_e as

$$\eta_e = \frac{\Delta l_1}{\Delta l_t} = 1 - \frac{\Delta l_0}{\Delta l_t}. \quad (2)$$

A further assumption is that the deformation of tissue is essentially due to a uniform tension applied over the cross section of the GI tract. Therefore, the stress in the tissue is

$$\sigma = \frac{F_c}{\pi \Phi t}. \quad (3)$$

The related strain, from (1), is

$$\varepsilon = \sqrt{\frac{F_c}{\pi \gamma \Phi t}}. \quad (4)$$

The strain may be regarded as the ratio

$$\varepsilon = \frac{\Delta l_0}{l_0} \quad (5)$$

where l_0 is the distance between the proximal clamp and the distal tip before the elongation occurs. Consequently, the following relation can be derived:

$$\Delta l_0 = l_0 \sqrt{\frac{F_c}{\pi \gamma \Phi t}}. \quad (6)$$

From (2) and (6), it may be concluded that

$$\eta_e = 1 - \frac{l_0}{\Delta l_t} \sqrt{\frac{F_c}{\pi \gamma \Phi t}}. \quad (7)$$

If biomechanical properties of the GI tract are assumed not to vary, from (7) it can be seen that the efficiency of elongation is still primarily dependent on the stroke Δl_t of the device. A longer stroke would yield higher elongation efficiency. However, it is important to note that longer strokes are undesirable for navigating bends. A longer stroke would also give rise to longer cycle times and increases the stiffness of the device. It is also noted that η_e depends on F_c . The lower F_c is, the higher η_e would be. Fortunately, the frictional component of F_c is dependent on the material and mechanical design of the distal head. It should be fabricated by materials with low coefficient of friction and geometrically designed so that it does not oppose the on-coming GI tissue. Air insufflation to preopen the lumen also drastically reduces F_c .

During retraction, only positive (traction) stresses arise in the GI walls supporting mesentery and (1) applies again: though the value of γ has to be purposely determined (in general γ of mesentery muscles could be different from γ of the colon)

$$\eta_r = 1 - \frac{l_0}{\Delta l_t} \sqrt{\frac{F_c}{\pi \gamma \Phi t}} \quad (8)$$

where l_0 now refers to the distance between the proximal end and the nearest proximal mesentery muscle that holds the GI tract in place. The value of γ is again related to the elasticity of the GI tissue, by considering the mesentery muscle rigid (this situation is strictly valid at the anus; in different regions of the GI tract the value of γ could be a combination of elasticity of mesentery and GI tissue). Fig. 2(b) illustrates how losses in retraction efficiency can occur due to the loosely constrained nature of the GI tract.

The modeling of the clamping mechanism is more straightforward as compared to that of the elongation and retraction mechanisms. The clamping force F_g is defined as the maximum adhesion force that the device can apply on the GI tissue in the longitudinal direction. The higher F_g is, the better the device attaches itself onto the GI tract. The rule of thumb is that if

$$F_g \geq F_c \quad (9)$$

then the single clasper is rendered effective. An efficient clasper would have a high value of F_g and is capable of grasping consistently onto the GI tissue. The clamping efficiency η_c is taken to be 100% as long as there is no slippage between the clasper and the GI tissue.

III. EXPERIMENTAL SETUP AND RESULTS

Fig. 3 shows a picture of an inchworm prototype used in the experiments. It measures 24 mm in diameter and has lengths of 115 mm and 195 mm when retracted and elongated, respectively. A flexible rubber bellow acts as the extensor that gives the device a stroke of 80 mm when extended. A mechanical and suction clasper is employed at both its distal and proximal ends. 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. Grooves were carved on the clamping walls to enhance the grip of the clasper. Five flexible air tubings, each of diameter 2 mm, exit from the proximal end of the device to form the “tail” of the inchworm device. These are connected to an external pneumatic distributor and a computer controls the activation of solenoid valves which are responsible for driving the extensor and claspers according. Working parameters like air pressures and time intervals can be easily monitored and modified from a human machine interface.

In vitro experiments were carried out by exploiting a “home-made” simulator made of polystyrene. This artificial path was patterned according to the indications of medical doctors in order to reproduce a



Fig. 3. Photograph of the inchworm prototype.

realistic three-dimensional structure of the human colon. A pig’s colon of length 150 cm was placed in the test bench and constrained at both its ends. The device was inserted in the colon and its performance was recorded both for the entire path and for each colonic tract (bend or straight path). Table I summarized the experimental results.

An *in vivo* experiment was carried out on a 35-kg male pig under general anaesthesia. The experiment was performed in an authorized laboratory, with the assistance and collaboration of a specially trained medical team in accordance to all the ethical considerations and the regulatory issues related to animal experiments. Prior to the experiment, the pig’s bowels were properly prepared for colonoscopy. A colonoscopy procedure using a conventional colonoscope was first performed by a skilled endoscopist to inspect the colon. Two bends in the colonic tract were revealed during the inspection. The first, a gentle bend, was situated about 30 cm from the anus while the second, an acute kink, was situated about 50 cm from the anus. After the withdrawal of the colonoscope, the prototype was introduced manually about 10 cm into the pig’s anus. Upon activation of the gait sequence, the inchworm device propelled itself a distance of 40 cm into the colon with an estimated speed of 0.19 cm/s. After which, its speed decreases and the device was observed to remain stationary 55 cm from the anus. The gait sequence was stopped and the device was retrieved by manually pulling its “tail.” A second inspection revealed that the device surpassed the first gentle bend without much difficulty. The head of the device reached a few centimeters after the second, more acute bend. This experiment showed the device’s capability of propelling itself into the part of the GI tract necessary for a rectum-sigmoidoscopy diagnosis. In terms of efficiency, since the theoretical speed can be calculated to be 0.25 cm/s, the locomotion efficiency of the device was 76% along the straight portion of the colon; then it decreased to zero during the navigation of the second curve. The prototype has demonstrated high elongation and clamping efficiencies, and showed its ability to traverse pass the rectum, sigmoid, and descending colon.

IV. DISCUSSION

In this paper, the authors illustrated their approach to the problem of “effective” locomotion in the GI tract and the critical analysis of “inchworm” locomotion devices, based on extensor and clasper mechanisms.

The inchworm type locomotion is analytically modeled by taking into account the interaction of locomotion devices with the locomotion environment. This model leads to the definition of a locomotive efficiency which can be used to predict and compare the performances of new device configurations analytically. In this way, it is possible to better interpret successful and unsuccessful experimental results and to extract important indications to improve and design effective locomotion devices for the GI tract.

This study leads to the design, fabrication and testing of a flexible locomotion device able to propel itself in the colon and to perform (when endowed with a video system) at least rectum-sigmoidoscopy (according to the *in vivo* test results).

During *in vitro* tests the inchworm prototype exhibits high locomotion efficiency in tissues laid in straight paths (over 80%), and is less effective in overcoming acute bends. However, the average efficiency is always more than 70%, even if considering curved paths. The minimum

TABLE I
SUMMARY OF *IN VITRO* TEST RESULTS

Description of paths	Time (s)	Distance (cm)	Speed (cm/s)	Efficiency
Straight, 2D path	95	20	0.210	84%
3D Curve of 80°, radius of curvature 12 cm, height of hump 5.5 cm	100	16	0.160	64%
3D Curve of 180°, radius of curvature 10 cm, height of hump 5 cm	182	31	0.170	68%
2D Curve of 84°, radius of curvature 12 cm	102	18	0.175	70%
Entire simulated path of colon	583	105	0.18	72%

radius of curvature surpassed by the device is 10 cm with a curvature angle of 180°. By considering a colon with a length of 150 cm, the recorded medium speed of 0.18 cm/s would allow a navigation time of less than 15 minutes. This result is in line with time taken to perform a conventional colonoscopy, which is approximately 15–20 minutes.

In the *in vivo* experiment, the inchworm prototype was able to propel only in the first tract of the colon. The analysis of the locomotion efficiency allows the interpretation of this behavior and to recognize the retraction phase as the most critical parameter. In fact, the elongation efficiency is roughly constant along the GI tract (in this case the colon) since all the parameters affecting it are practically constant (length of the device, stroke, impeding force for opening the lumen and overcoming the friction, tissue elasticity, etc.). Moreover, the clamping efficiency can be assumed to be constant, being always in the order of 100% whenever the tissue is being sucked and grasped by the claspers. On the other hand, the retraction efficiency depends on the location of the mesenteries. Therefore, the locomotion problems are caused mainly by the low retraction efficiency. In fact, when the device is in a part of the colon far from the anus (which is one of the strongest points of constraints for the colon), the efficiency decreases according to (8), where l_0 gradually increases.

The authors' future work will be mainly devoted to the improvement of the inchworm locomotion model by considering objectives parameters and characteristics of the GI tissue (measured *in vivo*) which are fundamental to interpret the interaction between tissue and locomotion devices. From a practical point of view, the improved model will lead to the design of inchworm prototypes with a higher retraction efficiency without affecting the already high elongation and clamping efficiencies.

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