Modelling and Experimental Validation of the Locomotion of Endoscopic Robots in the Colon

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Abstract. This paper concerns a biomechanical study to determine the efficiency of the motion of endoscopic robots in the colon. A quasi-linear viscoelastic model for soft tissues has been introduced to determine the mechanical behaviour of colon and mesenteries. A study of efficiency of the phases of the motion, through biomechanical and geometrical factors, has brought to calculate the critical stroke to perform motion inside intestinal walls. This study has furnished the guidelines to design an high-stroke pneumatic prototype for colonoscopy. In vivo tests have been performed with the fabricated prototype and have shown high efficiency of the robot in navigating inside pig's intestine.

1 Introduction to robotic colonoscopy

Minimally invasive techniques allow to make diagnoses by introducing advanced endoscopes in the human body through natural orifices or small incisions. In particular, the diagnosis of colon cancer is performed by using a colonoscope which has onboard a CCD camera, bundles of optical fiber for illumination and several working channels for local treatment and biopsy.

The traditional colonoscopes are pushed inside the human colon and when the medical doctor approaches an acute intestinal bend, he/she steers the endoscope tip in order to find the colon lumen and then he/she drag the colon in order to align the intestine with the colonoscope and to advance.

The introduction of a self-propelled device which generates just "internal" forces and which does not need any external pushing actions would improve the colonoscopy procedure in terms of patient pain reduction and easiness of advancement.

On the other hand, semi-autonomous colonoscopy poses several problems: no external references exist and the poorly supported intestine is deformed when "internal forces" are generated in order to obtain a self-propelled solution; this deformation makes difficult to overcome acute bends and to advance at all.

This abstract describes the approach to the problem of the effective advancement in the gastrointestinal tract with no or negligible losses and it propose a preliminary model to design endoscopic robot with the efficient stroke and the right flexibility for the tortuousness of the human colon.

2 The background: propulsion mechanism based on the "inchworm" locomotion

For the locomotion in the human colon, the authors have exploited an inchworm device [1]. It consists of two clampers at its ends and one extensor at its mid section. The clamper is used to adhere or clamp the device onto the substrate while the extensor generate the stroke required for the advancement. Currently the implemented solution consists of a pneumatic bellow (the extensor) and two clamping mechanisms which suck the tissue and then grasp it by closing two opposite jaws. Some service tubes for the suction and the pressure are located inside the robot and they constitute the tail of the robot.

A scheme of the inchworm locomotion and a typical inchworm prototype are shown in Figure 1.

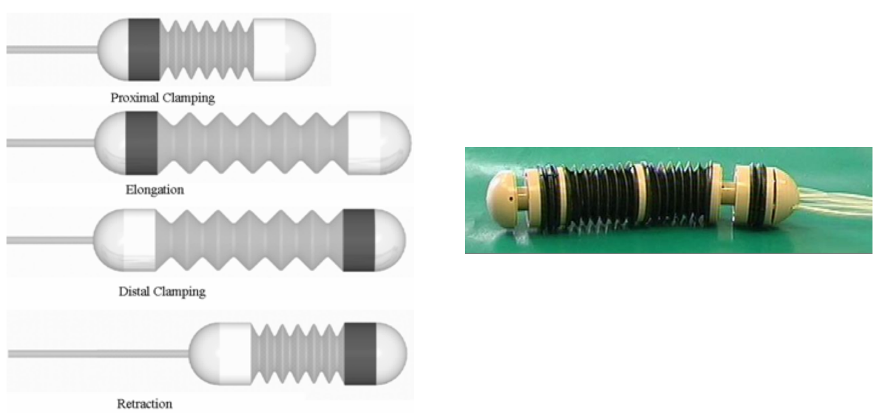

Fig. 1. Typical inchworm motion and typical inchworm prototype

Basically, the stroke should be the difference in length of the extensor in its elongated and retracted states. On the other hand, even if each inchworm phase is efficient by itself, some stroke losses are generated by the deformation of the colon tissue during the elongation and by the elasticity of the mesentery muscles during the retraction phase.

The following sections will describe the modelling of the retraction and elongation phases of the robot.

3 Viscoelastic modelling of intestinal soft tissues

The first step for an efficient design of a robotized endoscope concerns the determination of the time-dependant response of intestinal tissues to a generic external action in terms of force or displacement [2]. In particular the study has to be focused on the biomechanical properties of intestinal walls and mesentery, being the biological interface of the device the first and its anatomical support the second.

The goal of this section is to determine a constitutive equation for the tissues at a macroscopic scale, at the same order of endoscopic stroke.

Experimental tests have been performed with freshly removed *in-vitro* strips of porcine intestinal segments and a viscoelastic model has been formulated.

To evaluate experimental data the instruments of finite deformation mechanics, in terms of strain and stress tensors, have been introduced [3].

The biotribological properties of the tissue, investigated in [4], allow to consider the shear stress negligible; a tissue strip has been so considered as a bidimensional, uncompressible and orthotropic body with a non-linear mechanical behaviour.

After few load cycles the tissues have shown a repeatable stress-strain curve; if preconditioned they have been treated as pseudo-hyperelastic solids [3], and an expression for a *pseudo-elastic strain energy density* ρW has been individuated for both loading and unloading.

The stress in the intestinal tissue is function both of the time and of the elongation imposed. Separating these variables and using the superposition principle for an arbitrary deformation we obtain a quasi-linear viscoelastic model of the tissues [5]:

$$\mathrm{T(t)} = T^{(e)}[\lambda(\tau)] + \int_0^{\mathrm{t}} T^{(e)}[\lambda(t-\tau)] \frac{\partial G(\tau)}{\partial \tau} d\tau \tag{1}$$

in which λ is the deformation imposed, $\mathrm{T}^{(\mathrm{e})}(\lambda)$ the *elastic response* and G(t) the *reduced relaxation function* [5].

Eq.(1) imposes that the complete quasi-linear viscoelastic characterization needs traction and relaxation tests to determine $\mathrm{T}^{(\mathrm{e})}(\lambda)$ and G(t) respectively.

Traction tests lead to the determination of ρW through interpolation of stress-strain relation for an hyperelastic solid [3]. Its mathematical expression follows the pattern indicated in [6]:

$$\rho W = \frac{c}{2} e^{Q} + P; \tag{2}$$

where $Q = a_l E_l^2 + a_\theta E_\theta^2$, $P = \frac{1}{3}\left(b_l E_l^3 + b_\theta E_\theta^3\right) + \frac{1}{2}\left(d_l E_l^2 + d_\theta E_\theta^2\right)$, $\mathrm{E_i}$ represent Green strain tensor's components [3], and the others are dimensional coefficient to be determined through experimental data interpolation.

Traction tests have also shown that the hysteresis spectrum is flat over a wide range of strain rate. This consideration allows to obtain an analytical expression of G(t) integrating infinite Kelvin models and fixing a constant hysteretic value for a known strain-rate range [5].

Relaxation tests show for the examinated tissues that G(t) has a constant slope inside the range of flat hysteretic spectrum:

$$G(t) = \Re \cdot \log(t) + d \tag{3}$$

with $\Re = -c\left[1 + c \ln \frac{\tau_2}{\tau_1}\right]^{-1}$ for $\tau_1 < t < \tau_2$, in which $1/\tau_1$, $1/\tau_2$ are the boundary frequencies of the range, and c,d are constant values.

4 Determination of the endoscopic critical stroke to perform self-motion inside intestinal walls

The study of locomotion efficiency of endoscopic devices, such as the one designed in [1], concerns the efficiency of technical solutions in every phase of the motion and in every segment of the intestinal walls to investigate.

In the inchworm locomotion three inefficiencies can be basically underlined:

- Stretching of the tissue during forward advancement
- Dragging of the tissue during retraction (“*Accordion Effect*”)
- Weak and/or void clamping

Let the *locomotion efficiency* η be the rate between effective and theoretical advance:

$$\eta = \eta_e \cdot \eta_r \cdot \eta_c = \frac{effective\ advance}{theoretical\ advance} \tag{4}$$

where η_r, η_e, η_c are the elongation, retraction and clamping efficiency respectively.

Considering the holding force of the clamping devices largely enough to allow the necessary traction force [7], clamping efficiency is practically not influential to evaluate η.

The theoretical study of the elongation and retraction phases of the endoscopic motion leads to an index of the global efficiency of the device and to very useful guidelines for the design of more effective robotized prototypes.

4.1 Elongation efficiency

Let the *elongation efficiency* η_e be the rate between the effective advance made by the robot in the elongation phase and the theoretical advance allowed. In mathematical terms it can be expressed by:

$$\eta_e = \frac{effective\ advance}{theoretical\ advance} = \frac{d - d_{cr}}{d} \tag{5}$$

where d and d_{cr} are the effective and the critical stroke of the device in elongation.

The critical stroke d_{cr} represents the lowest value of the stroke that allows an advance: elongating the endoscope tends to stretch the segments of intestine and mesentery between its clamping heads, with the traction force transmitted through the contact with the intestinal walls.

By considering the tissues with pseudo-elastic behaviour, as previously described, the critical stroke is the value that makes the pseudo-elastic response of the tissues in the contact point with the endoscope exactly of the same value of the traction force.

In order to evaluate an upper limit of the traction force, we consider an *interference* Δ between endoscopic and intestinal walls for a length b of the device. Let the intestinal geometry be circular [2] of diameter D_c and μ_{st} be the value of the static friction [4] (Figure 2).

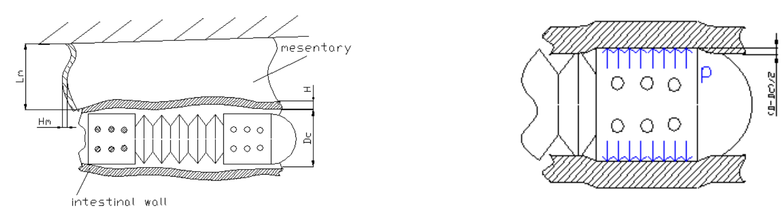

Fig. 2. Modeling of the elongation phase (on the left); interference during elongation (on the right)

The interference Δ will generate a pressure p in the segment of intestine in contact with the distal clamping, and a radial strain ε_θ in the intestinal wall given by:

$$\varepsilon_\theta = \frac{2 \cdot \pi \cdot (r + \Delta) - 2 \cdot \pi \cdot r}{2 \cdot \pi \cdot r} = \frac{2 \cdot \Delta}{D_c} \Rightarrow \varepsilon_\theta = \frac{2 \cdot \Delta}{D_c} \tag{6}$$

Being σ_{i} and σ_{m} intestinal and mesenteric lagrangian stress [3] respectively, the radial and axial equilibrium equations give:

$$2\sigma_{\theta i} \cdot H = 2 \cdot \int_0^{\pi/2} p \cdot r \cdot send\theta = D_c \cdot p \Rightarrow \sigma_{\theta i} = \frac{p \cdot D_c}{2 \cdot H} \tag{7}$$

$$\sigma_{zi} \cdot H \cdot \pi \cdot Dc + \sigma_{zm} \cdot H_m \cdot L_m = \mu_{st} \cdot \mathrm{p} \cdot \mathrm{D}_c \cdot \pi \cdot b \tag{8}$$

where H, $\mathrm{H_m}$ and L, $\mathrm{L_m}$ are the thickness and the length of intestine and mesentery respectively.

Through the constitutive pseudo-elastic equation, being the radial strain very small:

$$\sigma_{\theta i} = \frac{\partial(\rho W)_i}{\partial E_{\theta i}} = \mathrm{c} \cdot \mathrm{a}_\theta \varepsilon_\theta \mathrm{e}^Q + b_\theta \varepsilon_\theta^2 + d_\theta \varepsilon_\theta \approx b_\theta \varepsilon_\theta^2 + d_\theta \varepsilon_\theta \tag{9}$$

Substituting the constitutive equation in the expression of radial equilibrium [7] we find the interference pressure p:

$$p = \frac{2 \cdot H}{D_c} \cdot \left[b_\theta \left(\frac{2 \cdot \Delta}{D_c} \right)^2 + d_\theta \frac{2 \cdot \Delta}{D_c} \right] \tag{10}$$

and from axial equilibrium (8):

$$(b_{zi}\varepsilon_{zi}^2 + d_{zi}\varepsilon_{zi}) \cdot H \cdot \pi \cdot Dc + (b_{zm}\varepsilon_{zm}^2 + d_{zm}\varepsilon_{zm}) \cdot H_m \cdot L_m = \mu_{st} \cdot \mathrm{p} \cdot \mathrm{D}_c \cdot \pi \cdot b \tag{11}$$

Introducing finally the congruence of the entire deformation:

$$\varepsilon_{zi} = \varepsilon_{zm} = \frac{d_{cr}}{L} \tag{12}$$

The solution of a pseudo-elastic problem of finite deformation mechanics is given putting together constitutive equations, equilibrium and congruence; substituting (12) in (11) one obtains:

$$\begin{aligned} &\left[b_{zi} \left(\frac{d_{cr}}{L} \right)^2 + d_{zi} \frac{d_{cr}}{L} \right] \cdot H \cdot \pi \cdot Dc + \left[b_{zm} \left(\frac{d_{cr}}{L} \right)^2 + d_{zm} \frac{d_{cr}}{L} \right] \cdot \\ &\cdot H_m \cdot Lm = \mu_{st} \cdot \frac{2 \cdot H}{D_c} \cdot \left[b_\theta \left(\frac{2 \cdot \Delta}{D_c} \right)^2 + d_\theta \frac{2 \cdot \Delta}{D_c} \right] \cdot Dc \cdot \pi \cdot b \end{aligned} \tag{13}$$

from which it's possible to find the value $\mathrm{d_{cr}}$ of the critical stroke in elongation.

Once known the geometry of the endoscope and the exact anatomy of the human intestine it's so possible to obtain an higher approximation of the critical stroke and a lower approximation of the elongation efficiency of the device.

4.2 Retraction efficiency

As discussed in the previous paragraph, let the *retraction efficiency* η_r be the rate between the effective advance made by the robot in the retraction phase and the theoretical advance allowed:

$$\eta_r = \frac{effective\ advance}{theoretical\ advance} = \frac{d - {d_{cr}}^r}{d} \tag{14}$$

In retraction the device tends to drag the intestinal tissue and the linked mesenteric strips creating an *accordion effect* ; $\mathrm{d}_{\mathrm{cr}}^{\mathrm{r}}$ is the value of the minimum critical stroke to avoid this effect and perform an advance.

By using the same hypothesis of the elongation problem, the difference is that now intestine becomes compressed and has no stiffness. To obtain a lower approximation of the mesenteric pseudo-elastic force, we consider the longitudinal stiffness of an equivalent mesenteric strip of length b and 45 oriented on the longitudinal direction (Figure 3).

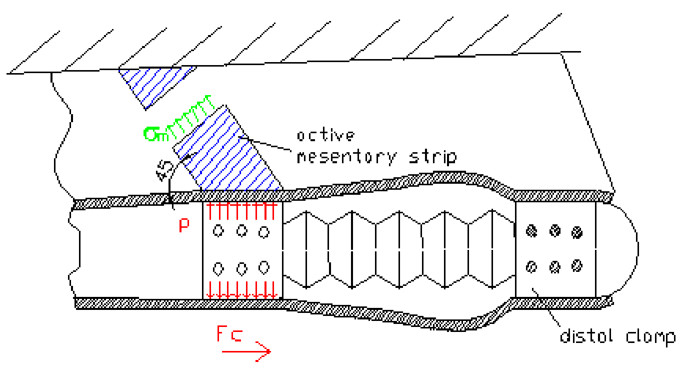

Fig. 3. Modeling of the retraction phase

The problem of finite pseudo-elastic deformation is solved by:

$$Constitutive\ equation \qquad \sigma_{zm} = \frac{\partial(\rho W)_{zm}}{\partial E_{zm}} = \mathrm{b_{zm}}\varepsilon_{\mathrm{zm}}^2 + \mathrm{d_{zm}}\varepsilon_{\mathrm{zm}} \tag{15}$$

$$Congruence\ of\ deformation \qquad \varepsilon_{\mathrm{zm}} = \frac{\mathrm{fd} \cdot \mathrm{d}}{\sqrt{2} \cdot Lm} \tag{16}$$

Longitudinal equilibrium $\sigma_{zm} \cdot \frac{b}{\sqrt{2}} \cdot h_m \cdot f_{zm} = \mu_{st} \cdot p \cdot D_c \cdot \pi \cdot b$ (17)

where:

$f\mathrm{d} = \sqrt{1.5^2 + 1} - \sqrt{2} =$ *corrective factor of deformation* (cautelative for d > 0,5 Lm);
$f_{zm} = \frac{1}{\sqrt{2}} =$ *corrective factor of load.*
The critical minimum stroke to avoid accordion effect is so given by putting together (10,15,16,17):

$$f_{zm} \cdot \left[b_{zm} \left(\frac{f_d \cdot d}{\sqrt{2} \cdot L_m} \right)^2 + d_{zm} \frac{f_d \cdot d}{\sqrt{2} \cdot L_m} \right] \cdot \frac{b}{\sqrt{2}} \cdot h_m =$$

$$= \mu_{st} \cdot \frac{2 \cdot H}{D_c} \cdot \left[b_\theta \left(\frac{2 \cdot \Delta}{D_c} \right)^2 + d_\theta \frac{2 \cdot \Delta}{D_c} \right] \cdot Dc \cdot \pi \cdot b \tag{18}$$

¿From this relation we find that the critical minimum stroke to avoid accordion depends on the shape of the endoscopic device, the intestinal geometry in which it operates, the tribological and viscoelastic properties of the gut tissues.
Once known these parameters one obtains an higher approximation of the critical stroke and a lower approximation of retraction efficiency of the device.
It's important to put in evidence in this case that the length of the device doesn't influence the value of the critical stroke.

5 Numerical results, design guidelines and preliminary prototype

In order to calculate practical values of the critical minimum stroke needed by an endoscopic device with inchworm locomotion, we consider the geometrical data of the robotized endoscope described in [1] and the biomechanical properties of porcine intestine obtained in the previous section.
By substituting this value in the equations (13) and (18), one obtains:

Elongation phase $d_{\mathrm{cr}} = 0,16 \cdot L$ (19)

Retraction phase $d_{\mathrm{cr}}^{\mathrm{r}} = 1,9 \cdot L_{\mathrm{m}}$ (20)

in which L and L_{m} are the length of the endoscope and of the mesentery respectively.

By considering that L is about 10 cm and L_m is about 5-10 cm, the critical stroke depends essentially on the retraction relation: a big stroke is necessary to perform motion with a good efficiency.

Furthermore the equations (13) and (18) allow an analysis of sensitivity on the geometrical, biomechanical and anatomical parameters that influence the efficiency of the motion; these are the guidelines for a correct and efficient design of a robotic endoscope .

A pneumatic prototype has been fabricated following the guidelines taken from the biomechanical analysis. The robot is made of four bellow and has the following characteristics:

retracted phase length	= 11.5 cm
stroke length	= 11.5 cm
stiff part length	= 3.2 cm
effective stiff part length	= 3.7 cm
theoretical speed	= 18.65 cm/min
elongation ratio	= 200%

The so described robot is shown in figure 4.

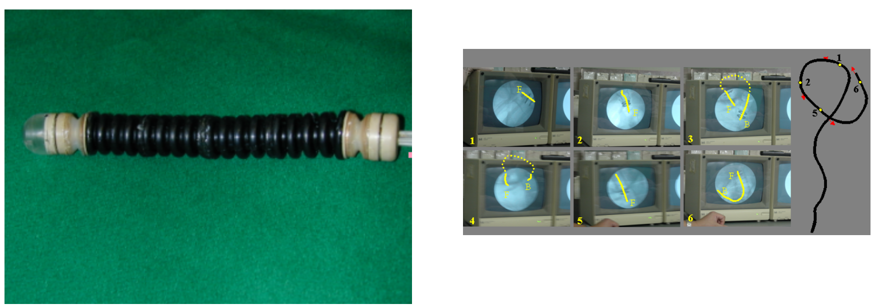

Fig. 4. The four-bellow robot and the travelled path in the intestine as visible by fluoroscopy

In-vivo tests on pigs have been performed at IMC in Seoul with this prototype. The robot has navigated 90 cm in pig's intestine (measured from the robot tip). The procedure took about 10 minutes, the most part to overcome an acute bend existing in pig's intestinal anatomy.

The robot arrived at the same point achieved by the traditional colonoscope. However, on the basis of the fluoroscopy images, the traditional colonoscope appears to deform all the intestine, while the robot deforms the intestine just locally, that could be an advantage in terms of pain for the patient.

In conclusion this study has brought to the design and the fabrication of an high-stroke prototype able to reach the same performances, in terms of navigated length, of a traditional colonoscope, and having an higher motion efficiency if compared to the other existing semiautonomous robots.

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