Abstract—While the progress in imaging techniques more and more allows early and accurate diagnosis, minimally invasive intervention is still largely dependent on the availability of smart tools able to perform tasks inside the human body with a high level of autonomy. In this framework, endoscopic robots locomotion capabilities are needed to reach the site of interest, possibly with the desired orientation and with a firm grasping of the tissue. Current locomotion techniques do not provide sufficient degrees of mobility or are hardly miniaturizable to the desired extent. In this paper we present the concept of a novel locomotion technique, called pinch locomotion, that relies upon and takes advantage of the large deformability of intestine to allow propulsion, steering and standing at a place with a continuous grasping of the tissue. The proposed locomotion technique is instantiated in a preliminary larger-scale prototype (70 mm × 29 mm × 10 mm), that is able to easily propel itself over a flexible stripe of cloth. The feasibility of a miniature endoscopic robot, endowed with the pinch-locomotion and with dimensions compatible to current swallowable devices, is also investigated from a design perspective.

I. INTRODUCTION

Digestive endoscopy is a modern branch of gastroenterology that allows the diagnosis of digestive tract diseases. Gastroenterology comprises colonoscopy, which investigates the tract of intestine from the anus to the caecum, and gastroscopy, which targets stomach and oesophagus. Colonoscopy and gastroscopy employ flexible endoscopes respectively inserted through the anus and the mouth. None of them are capable of reaching the small intestine [1], whose diseases have been largely undiagnosed till recent years.

The disadvantages related to current diagnostic practices, which are uncomfortable for the patient and sensitive to the operator’s skill, have stimulated the research on a novel branch of biomedical robotics centred on the development of autonomous endoscopic miniature robots able to propel themselves along the intestine. A historical perspective on this field is provided in [10].

In 2000 Given Imaging [3], [4] presented M2A, the first endoscopic capsule integrating a CMOS camera, drawing the attention of the medical community on the radically new diagnostic possibilities enabled by miniaturization technology. Although the device can be theoretically tracked and stopped at a specific site by means of external magnetic devices, its limited motion capabilities appear to strongly limit its potential in therapeutic applications requiring, e.g. localized drug release, tissue sampling, cutting or suturing [3], [4]. However, stopping at a site and turn in place while keeping a constant grip on the tissue is still an open challenge. Moreover, the mechanical complexity of current solutions asks for a dramatic miniaturization of a large number of 3D parts, with issues related to assembly complexity and reliability.

In this paper we present the concept of a novel locomotion technique, called Pinch Locomotion, that addresses all the challenges listed before, namely: dexterous mobility and mechanical simplicity.

A peculiar feature of this new technique is that it takes advantage of what is usually considered among the most adverse features of gastrointestinal tissues, i.e. their remarkable deformability. The pinch locomotion principle, described in Section III, is expectedly able to overcome the limits of current locomotion techniques, shortly recalled in Section II. For a preliminary validation of the locomotion technique, a prototype, described in Section IV, has been developed, which is able to locomote over a stripe of slack cloth. A detailed feasibility study of an endoscopic robot exploiting the pinch locomotion is finally presented in Section V.

II. STATE OF THE ART

The need of an effective locomotion system for endoscopic robots promoted the investigation of diverse solutions that, for clarity purpose, we group into two families. The first one includes devices that are externally driven, while the second family refers to devices that autonomously locomote inside the human body, thanks to suitable kinematic and actuation solutions.

As it regards the first family, it basically relies on external electromagnetic fields generated by coils or movable permanent magnets. Since 1998 at RF SYSTEM Lab, Nagano (Japan), the Norika Project Team has been dealing with magnetic actuation of robotic capsules. Three coils are placed inside the capsule, acting as rotor coils, while three coils, embedded in a vest-like jacket, act as stators. The direction of stator magnetic field sets the rotation axis [5], [16].

A self-propelled capsule that exploits the variation of a uniform magnetic field, generated by three pairs of opposing electromagnets in order to obtain the desired position and orientation of the device, has been presented in 2004 by Olympus [5],[15]. An alternative solution, comprising two permanent magnets, respectively embedded in the capsule and manipulated by a robot, has been presented by Kim at al.[10] [14]. The external magnet is connected to a 2 DOF rotary wrist of a

Pinch Locomotion: A Novel Propulsion Technique for Endoscopic Robots

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Cartesian robot. Localization of the capsule is achieved by means of Hall sensors.

The second family (i.e. autonomous locomotion) groups a number of different principles that, thanks to an expectedly higher dexterity, promise advantages such as an accurate control on the trajectory, necessary for safely overcoming critical areas, and good adaptability to changing organs shape.

The legged locomotion [5], [6], [7], [13] make use of - usually bioinspired- multi-articulated actuated legs, while the inchworm locomotion [9] [10] [11] takes inspiration from the caterpillar of the geomter moths and is based on alternating sequences of extension and contraction of a body mounting two distal clammers for grasping the tissue.

M. Sitti et al. [19] proposed techniques to fabricate synthetic gecko foot-hairs, as dry adhesives, to obtain surfaces able to adhere to the mucosa of various organs such as that of the gastro-intestinal tract.

In [20] they apply this technique to a robotic capsule equipped with three actuated legs with compliant adhesive feet.

A locomotion system, based on a rotating rib is described in [17]

Another interesting approach is that proposed in [21], where the robotic capsule is moved through electrical stimulation.

Although quite diverse in the exploited principles, all the above mentioned locomotion techniques show one or more of the following drawbacks:

- Difficulties in maintaining the tissue grasped and to keep the position against peristaltic waves;
- Difficulties in rotating in loco;
- Difficulties to change direction during locomotion;
- High mechanical complexity;
- Need of equipments and tools around or over the patients (i.e. magnetic jackets, robotic manipulator) in order to localize and move the robotic capsule from outside the body [5].

To our opinion, the pinch locomotion has the potential to overcome all of the above mentioned drawbacks, by taking advantage of the large deformability of gastrointestinal tissues, as better described in Section III.

III. PRINCIPLE OF THE PINCH LOCOMOTION

The idea behind the proposed locomotion principle can be presented, abstractly, by imaging two wheels, both tangent to the mucosa (Fig. 1-A), connected to each other by an elastic element that allows the adjustability of their interaxis.

Supposing an adequate friction between the wheels surfaces and the tissue, when the two wheels counter-rotate the outer layers of the tissue are forced to enter the space between the wheels, thus being pinched. The elastic element allows proper room between the wheels. In this configuration, when the wheels rotate at the same angular speed, a translation is produced, with the pinch waving over the tissue surface. The system shown in Fig.1-A, consisting of only a couple of wheels, is just able to theoretically move back and forth, with no turning capability.

By mounting another module, comprising an identical couple of wheels, in parallel to the former one, turning and steering can be produced by driving the two modules at different translational speeds (Fig. 1-B).

IV. EXPERIMENTAL TESTING

The general principle shown in fig. 1 can be practically embodied in several different designs, depending on the features of the robot to be developed (e.g. shape and weight) and on the available technologies for fabrication, actuation, etc.. In the following, we present a large scale prototype where compliance is provided by a flexure joint (instead of a linear spring) and the wheels are substituted by a belt, that can be freely arranged around pulleys to shape the pinching tips as most convenient.

A. Design

A prototype corresponding to the module shown in fig. 1-A has been developed for testing the viability of the pinch
locomotion concept (fig. 2).

Actuation is demanded to two gearmotors (A) with a rated torque of $5.25 \times 10^{-3}$ Nm, and a zero-load speed of 600 rpm. The gearmotors are buried in rapid prototyped (Zprint 310 by ZeCorporation) frames (B) connected by a brass flexure joint (C) (Young modulus: $E = 90$ GPa; Length = 50 mm; Width = 10 mm; Thickness = 0.2 mm). The driving pulley (D) puts into motion a rubber belt (E), 1 mm thick, running over idle pulleys (F) supported by bearings lubricated by graphite powder. The pinching occurs in the region denoted by G, where the two elastic belts run around the pulleys placed at the sharp tips of the two frames. The radius of curvature of the surfaces performing the pinching is 2.7 mm.

Thanks to the flexure joint, the tips can passively move away from each other thus allowing the entrance of the tissue/cloth.

B. Experimental results

The evaluation of the capability of the prototype to pinch a tissue (phases 1. and 2. in fig. 1) and to actually apply a locomotive force (phase 3. in fig. 1) has been carried out on a purposively assembled treadmill (overall dimensions: 300 mm $\times$ 120 mm $\times$ 100 mm) in which a slack cloth stripe (width: 65 mm) is wrapped around two passively rotating shafts (fig. 3). One end of the cloth stripe is fixed to the treadmill frame, while the other end is connected to a cylinder (mass: 15 g) that can be freely lifted. The weight of the cylinder assures a constant tension of the cloth. During the tests, the prototype is held in place by a support (not shown in fig. 3).

During pinching, both motors are powered with the same voltage but with reversed polarity. Pinching occurs when the voltage is above 2.5 V. Nevertheless, a voltage of 3 V was used, because it allows a more repeatable behaviour.

The locomotion phase (phase 3. in fig. 1) theoretically requires the two motor units to rotate with opposite speeds. However, we got an experimental evidence that stable locomotion requires the front wheel to have a slightly higher speed than the rear one. This assures the permanence of the pinched tissue between the tips during the cloth motion.

The chosen embodiment of the pinch locomotion appears to be capable of producing a speed of up to 145 mm/sec, while keeping a constant grasping on the “ground” (cloth).

V. TOWARDS MINIATURIZATION

The prototype described in the previous section was assembled using off the shelves components. Anyhow, its dimensions are evidently incompatible with an intra-corporeal use. It is therefore mandatory to explore, from a design point of view, the feasibility of a miniature device, embedding two locomotion modules for turning/steering, whose dimensions should be compatible with those of existing endoscopic capsules. In particular, we aim at exploring the feasibility of endoscopic robots, exploiting the pinch locomotion, with dimensions similar to that of swallable systems. The investigation described in this section is also useful to point out the main technical challenges involved.

A. Evaluation of required torque

In order to properly dimension the actuation system, and particularly the necessary torque, an estimation of the order of magnitude of the forces that the robot and the tissue exchange is required.

Because of the low friction coefficients between common materials and the GI tissues ([8]), the torque required during locomotion is expectedly much lower than that required during the actual pinching phase, when both a deformation of the elastic organ and of the tissue occurs. Therefore, the maximum torque is requested during pinching.

An autonomous endoscopic robot has to withstand the dragging force ($F$) generated by peristalsis. Such force is expectedly dependent on the size, shape and frictional properties of the robot. To our knowledge, no method to theoretically evaluate $F$ is available in literature. Nevertheless, Menciassi et al. ([12]), considered that $F$ should be not larger than 0.5 N for robots having dimensions similar to those of the M2A ([3]).

Let $F_p$ be the pinching force, i.e. the compressive force applied to the tissue by the two pinching tips or wheels. The pinch is able to withstand the peristaltic force as long as $F < F_p$.

The schematic given in fig. 1-A shows that $F_p$ is provided by an elastic member. Therefore, a sufficient pinching force is achieved only by using a stiff enough spring. Evidently, the higher the stiffness, the larger the torque at each wheel required to deform the spring in order to ultimately allow enough room for the tissue. Moreover, a torque is also required to properly stretch the tissue to let it enter the space between the tips. In summary, during pinching a torque ($T$) must be applied to the wheels, which is the sum of two terms:

1) One due to the deformation of the elastic member ($T_e$);
2) the other one due to the stretching of the tissue being drawn between the wheels ($T_s$).

A detailed evaluation of $T_s$ is not trivial, since it depends in a complex manner from a number of biomechanical and biotribological parameters that are not known a priori. Therefore, we propose here a simplified calculation, based on energy considerations, that allows a rough estimation of the order of magnitude of the actuation torque.

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Fig. 3. Set-up used for the evaluation of the pinching and locomotion capabilities of the prototype.
According to [9], the stress-strain relation for the gastrointestinal tissue can be approximated by a quadratic law:

\[ \sigma = \gamma \varepsilon^2, \]

with \( \gamma = 5 \pm 1.5 \ M Pa \).

With reference to fig. 4, said \( L_0 \) the mean distance between the capsule and the mesenteries, acting as fixed points of the tissue, and \( r \) the radius of the equivalent wheel, a stripe of tissue undergoes a deformation given by \( \varepsilon = \frac{2r}{L_0} \). The deformation energy per unit volume is \( e = \int_0^\varepsilon \sigma \ dx = \frac{2}{3} \varepsilon^3 \).

The total deformation energy is \( E_V \), where \( V \) is the volume of stretched tissue, approximated by \( V \approx 2 \frac{L_0}{2} \frac{2}{3} w \) (\( w \) is the width of the stripe of stretched tissue, being of the same order of magnitude of the wheels’ width). By applying the proper substitutions one finally finds that the energy required for stretching the tissue is:

\[ E_s \approx \frac{32}{3} \frac{r^3}{L_0^2} \delta w. \]

The minimum value for \( E_s \) is attained when \( F_p = F = k \delta \). In this case:

\[ E_{s_{\min}} \approx \frac{32}{3} \frac{r^3}{L_0^2} F. \]

Since the minimum elastic energy stored in the spring is \( E_{c_{\min}} = \frac{F^2}{2k} \), a pinch requires that the actuator connected to each wheel provides a minimum mechanical work given by

\[ L_{\min} = \frac{1}{2} (E_{c_{\min}} + E_{s_{\min}}). \]

Said \( \Delta \vartheta \) the rotation angle of a wheel during a pinching (\( \Delta \vartheta \approx \pi \)), the minimum requested average torque \( T \) is:

\[ T \approx \frac{F}{k\pi} \left( \frac{16}{3} \frac{r^3}{L_0^2} w + \frac{F}{4} \right) \tag{1} \]

A preliminary estimation of the minimum torque allows, by increasing such value by a proper safety factor, to choose adequate motors.

**B. Design**

Evidently, the actual evaluation of \( T \) requires preliminary hypotheses on the design of the robot in order to assign the proper values to the parameters in (V-A).

The architecture taken into account is depicted in fig. 5. The pinching still occurs between two belts. In particular, with reference to fig. 5, the belt on the right is mounted over two pulleys with fixed axes. On the contrary, the submodule on the left includes an oscillating arm (e) connected to a torsional spring (f), allowing the adjustability of the pinch width. When the tissue enters the space between the tips, the oscillating arm rotates, thus compressing the spring.

The upper pulley (g) mounted on the same arm is positioned in such a way that the belt tension remains almost constant during the arm rotation.

By assuming: \( k = 0.17 \times 10^{-3} \ \text{Nm} \), \( L_0 = 60 \ mm \), \( r = 1.2 \ mm \), \( w = 1.2 \ mm \), we get: \( T \approx 0.79 \times 10^{-3} \ \text{Nm} \).

Smoovy motors (\( \phi 1.9 \ mm \)) with planetary gearhead (\( \tau_1 = 47 : 1 \)) provide a nominal torque of \( 0.28 \times 10^{-3} \ \text{Nm} \) at a rated speed of 2100 rpm. By adding a worm gear with reduction ratio \( \tau_2 = 18 : 1 \) the torque is increased to \( 5.0 \times 10^{-3} \ \text{Nm} \), which exceeds the value estimated by (V-A) by a safety factor of \( \approx 6.4 \). Such a high SF takes care of the uncertainties of the model, as well as of the loss of kinematic efficiency in the gear train.

The worm gear reduced the nominal rotational speed to 117 rpm. Considering the radius of the driving pulley (\( R = 3.5 \ mm \)), the theoretical locomotion is 86.8 mm/s. Such a value allows a whole GI tract inspection in about \( 30 \div 35 \ \text{min} \).

As explained in Sec. III, full robot motility requires two locomotion modules to be mounted on the side of the robot. The proposed design, shown in fig. 6, has a diameter \( \phi = 13 \ mm \) and a length \( l = 31 \ mm \). About the 60% of the internal volume of the capsule is empty and available for the

**Fig. 4.** Simplified scheme for the evaluation of \( T_s \).

**Fig. 5.** A: overview of the design of a miniature module (motors: reduction gear, belt tensioner and torsional spring). B: exploded view of the module.

**Fig. 6.** A concept drawing showing how the locomotion modules can be integrated into a robotic capsule.
allocation of batteries and other systems (e.g. vision, control, telemetry, etc.).

C. Energetic Analysis

Powering is one of the main challenges in the development of autonomous robotic capsules, because of the relatively low energy density of currently available batteries. The actual power consumption strongly depends on the locomotion features (e.g. tissue properties; efficiency of the adhesion mechanism; displacement against peristalsis, etc.). A preliminary assessment of the absorbed current of each motor and of the efficiency of the reduction gear, which is estimated to be about 5% (50% efficiency of the planetary gearbox according to the manufacturer; 10% estimated efficiency of the worm gear), led to the choice of Polymer Li-ion technology. In particular a thin flexible battery (Geb PGE8014461, thickness: 1 mm), with a capacity of 74.52 mAh/mm², appears to be a suitable choice, since it can be wrapped around the inner empty surface of the capsule. The coiled battery would occupy a volume of about 1970 mm³ and would allow a minimum estimated autonomy of 7 min. Taking into account battery’s volume, the residual empty volume inside the capsule is still about 40% of total inner volume. According to the overall system design, additional batteries may be housed in the capsule, as well as dedicated powering systems for other modules.

VI. CONCLUSIONS AND FUTURE WORKS

This paper addresses the field of locomotion strategies for endoscopic robots and proposes the concept of a novel technique named pinch locomotion. What mainly distinguishes pinch locomotion from other strategies is its capability to keep a continuous grasping of the tissue. This is achieved by advantageously exploiting what usually is considered as a major challenge posed by the biomechanical properties of the GI tissues, i.e. its great deformability.

A prototype exploiting pinch locomotion has been developed and tested on a slack stripe of cloth, showing that the compliant tissue can be pinched using the proposed approach and that a propulsive force can be applied to the tissue through such a pinch. Such performance has been demonstrated over a slack cloth, where other locomotion techniques used in endoscopic robotics usually encounter significant performance issues.

The feasibility analysis of an endoscopic robot, with dimensions similar to those of swallowable systems, has been performed by designing a possible embodiment based on off-the-shelves components, such as the Smooovy micromotors and a flexible polymer Li-ion battery. Even if the complete locomotion system requires 4 motors for locomotion and steering, the design suggests that all the necessary components can be assembled inside the body of the capsule, still with a significant residual volume (about 40%). This result is very promising because, still now, no alternative locomotion technique is available that is so space saving. As an example, in [18] the mechanical parts required for locomotion occupy the whole volume of a capsule, while batteries are hosted in a tethered appendix. Although the aim of this paper was to present the idea of a novel locomotion strategy suitable to actuate endoscopic robots, we should like to mention the major issues that will be faced in future work to actually develop a working prototype.

A first issue is related to power supply. The energetic analysis underlined that current batteries are still far from allowing the desired autonomy. Taking into account only the power consumption of the locomotion system, and neglecting the energy needs of other modules, such as telemetry and vision, not taken into consideration in this paper, the maximum estimated autonomy is of about 7 min, while a full GI inspection expectedly takes at least 30 min. It is worth mentioning, anyhow, that pinching can be held with no further energy absorption, since the pinching force is provided by a passive spring.

The second issue is related to achieving a sufficient friction between the pinching surfaces and the pinched mucosa. Under this regard, we consider very promising the approach demonstrated in [11], where it is shown that micro-hooks can be used to gently grasp the tissue with the infliction of highly tolerable micro-lesions.

The last issue, arisen during the experimental tests with the fabricated prototype, regards the control of the tangential speed of the pinching surfaces. We already mentioned that, during locomotion, the front wheel must be faster than the rear one, with a difference in velocity that is expectedly dependent on the (non constant) biotribological properties of the GI tissue. Therefore, we expect that proper sensors will be required to regulate such speeds.

Although the paper focuses on the field of endoscopic autonomous robots, because it probably represents the advanced frontier of endoscopy, research on robotic systems, such as colonoscopies, may also greatly benefit from the availability of a novel locomotion technique.

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