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Bio-inspired solutions for locomotion in the gastrointestinal tract: background and perspectives

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This paper illustrates a bio-inspired approach to effective, smooth and safe navigation in the human body and, in particular, in the gastrointestinal tract. This idea originates from the medical need to develop more powerful tools for microendoscopy, which is one of the most challenging frontiers of modern medicine. Understanding motion and perception systems of lower animal forms, such as parasites, worms, insects and snakes, can help to design and fabricate bio-inspired robots able to navigate in tortuous, slippery and difficult-to-access cavities of the human body. A preliminary study of a biomimetic adhesion system for the human tissues is presented in this work and some technological implementations are illustrated and discussed. Finally, some issues concerning the goals of smart and reactive locomotion are considered and the most promising and relevant enabling technologies are discussed.

Keywords: endoscopy; biomimetic locomotion; smart actuators

1. Introduction and motivation

From a medical standpoint, the improvement of techniques for the endoscopic access to the digestive tract is of paramount importance for early detection of diseases. If detected at an early stage, most cancers of the human gastrointestinal tract can be treated by means of local resection of the diseased tissue. In order to improve the early detection of cancer, endoscopic screening is the most powerful tool. However, traditional endoscopy is usually accompanied by discomfort and pain, which limit the overall acceptance of screening endoscopy among healthy individuals. This is particularly true for colonoscopy (Cotton & Williams 1990; Miller *et al.* 1996).

A traditional colonoscope works as a volumetric pump: the pushing action performed by the endoscopist is transformed directly into a real advancement of the colonoscope inside the intestine. When the physician approaches an acute intestinal bend, he/she steers the endoscope tip in order to find the colon *lumen* (i.e. the free area) and then he/she stretches the colon from outside in order to align the intestine with the colonoscope and to advance.

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One contribution of 16 to a Theme 'Biologically inspired robotics'.

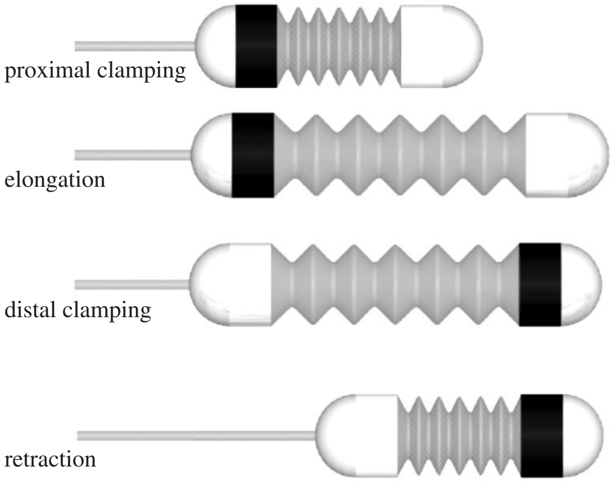

Figure 1. Schematic illustrating the sequence of the inchworm locomotion principle. The shaded area on the distal and proximal clamping actuators indicates the active clamping states.

Microendoscopy (i.e. endoscopy of the most remote, small and delicate regions of the human body) should allow a safe, painless and 'natural' access to the hidden and remote regions of the human body for diagnosis purposes, by exploiting microinstrumentation with a high degree of autonomy and endowed with 'flexible' locomotion.

2. Background activity

The problem of locomotion in the gastrointestinal tract was investigated with a distinctive engineering-driven approach, taking full account of the medical requirements: as the principal problems encountered in traditional colonoscopy originate from the quite rigid and heavy tail that is manoeuvred by the endoscopist in order to advance the active part of the device (the head) inside the colon, the main effort was devoted to transform that stiff and bulky tail into a flexible service tail. By service tail we mean a tube with no structural functions, but can be used for illumination, vision, water and air supply, insertion of tools for biopsy, etc. If a partly autonomous locomotion mechanism, capable of pulling the active head rather than pushing it from outside, could be implemented, this could reduce the painful manual procedures required by current endoscopy.

In line with other international research (Hirose *et al.* 1993; Phee *et al.* 1997; Treat & Trimmer 1997), we took inspiration from the locomotion of worms, whose 'working principle' is 'never let go of what you are holding until you are holding something else'. From a biological point of view, this locomotion model is used by the leech (Baader 1997; Skierczynki *et al.* 1996): although its body is segmented and its motion is the result of the displacement of each segment, the global locomotion can be quite simply described and artificially reproduced.

An inchworm locomotion device is made up of basically two types of actuators: clamper and extensor. The clamper is used to adhere or clamp the device securely onto the locomotion environment, while the extensor produces a positive displacement (known as the stroke, i.e. the difference in length of the extensor in its elongated

Figure 2. (*a*) Typical inchworm prototype with 'suction + clamping' mechanisms (diameter 24 mm; retracted length 115 mm). (*b*) Working principle of the clamping mechanism.

and retracted phases). The simplest inchworm device consists of two clampers at its ends and one extensor in the middle. Figure 1 shows the gait sequence of the forward propulsion (Dario *et al.* 1999).

Our first prototypes were actuated entirely pneumatically: the extensor consisted of a bellow and the clampers were two hollow cylindrical structures with numerous holes on their surface. A supplied vacuum caused the intestine tissue to be 'sucked' around the clamper, thus generating the traction forces needed for elongation and retraction in the intestinal tract.

Starting from this preliminary solution, several versions of the inchworm mechanism have been studied and implemented, by changing the actuation and the configuration of the clampers and the extensor. The most promising solution consists of the same pneumatic bellow (serving as the extensor) and two clamping mechanisms that suck the tissue and then grasp it by closing two opposite jaws (figure 2). This new clamping method overcomes the limitations of the previous vacuum clamping system, which was affected by slipping phenomena occurring at the interface between the device and the intestine (Phee *et al.* 2002*a*).

(*a*) *Limitations of a traditional mechanical solution*

The prototypes have been tested extensively *in vitro* and *in vivo*. The general conclusion that was obtained by these tests is that a purely mechanical solution is not appropriate for the design of real miniaturized autonomous adaptable navigation systems for the gastrointestinal tract. Most of the problems experienced in these prototypes related to the difficulty of 'perceiving' the local environment and then 'reacting' appropriately. For example, the closure of the jaws is regulated by a standard working cycle that is always the same for different conditions and configurations of the tissue. If the device was able to 'feel' when the tissue is collapsed within the jaws, the locomotion cycles would be more effective. The *feeling of the environment* can be reproduced by introducing traditional sensors (infrared, capacitive, etc.) and controllers, but this task becomes more and more difficult with shrinking the device, thus requiring an integrated approach.

Other important limitations were related to the external actuation, which make it impossible to obtain a real autonomous (and wireless) system, and to the size of the rigid parts of the device, which should be miniaturized as far as possible (2–3 cm^3) in order to simplify the navigation in the more constrained and tortuous regions of the intestine (Phee *et al.* 2002*b*).

The above considerations pushed the authors to face the problem of navigation in the intestine in a truly integrated way, by considering globally and at the same

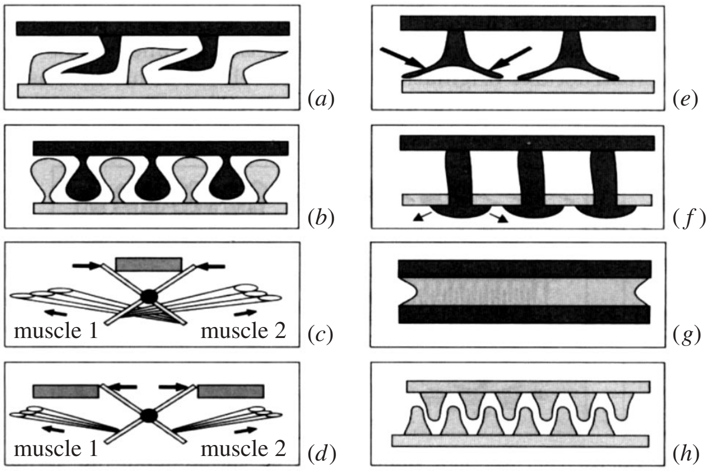

Figure 3. Eight fundamental classes of biological fixation principles: (*a*) hooks; (*b*) lock or snap; (*c*) clamp; (*d*) spacer; (*e*) sucker; (*f*) expansion anchor; (*g*) adhesive secretions; (*h*) friction. (Reproduced with permission from Scherge & Gorb (2001).)

stage all problems related to the actuation, the sensing system, the controller and the mechanisms. Just as in living creatures (even the simplest ones), the locomotion device must be designed as an integrated smart system where structural, actuation and sensing functions are fused and harmonized.

3. Locomotion and adhesion: solutions from nature

The most critical point in any locomotion mechanisms is related to the *adhesion* on the substrate, where adhesion can mean friction, grasping, attachment, etc. For example, in the inchworm mechanism, when a stable adhesion is realized, the locomotion can happen by exploiting a simple periodic elongation. The strategies adopted in nature to perform locomotion rely on a wide variety of ingenious mechanisms, such as dynamic adhesion, suction, adaptation to surface profiles, etc. Figure 3 illustrates a scheme of the main adhesion and attachment mechanisms exploited by most molluscs, parasites and worms and also plants (Scherge & Gorb 2001). In many cases, the adhesion is produced by a peculiar geometry that enhances the mechanical interference.

Both 'ciliated' (or hairy) and smooth interface structures can be adequate for the adhesion task: for example, many crickets (Scherge & Gorb 2000) are endowed with attachment pads that are flexible micromechanical units capable of self-adjusting to different scales of surface roughness. On the other hand, smooth and unstructured surfaces often covered by sticking mucus can be suitable to adhere onto different substrates, such as in the locomotion of snails (figure 4).

The analysis of force interactions and of the effectiveness of the tiny biological structures of attachment is one of the most recent trends of interdisciplinary research in animal biology (Autumn *et al.* 2000; Dickinson *et al.* 2000). Therefore, the biomechanics and biotribology of animals can provide very useful specifications for the development of artificial structures and subsystems for performing attachment, and

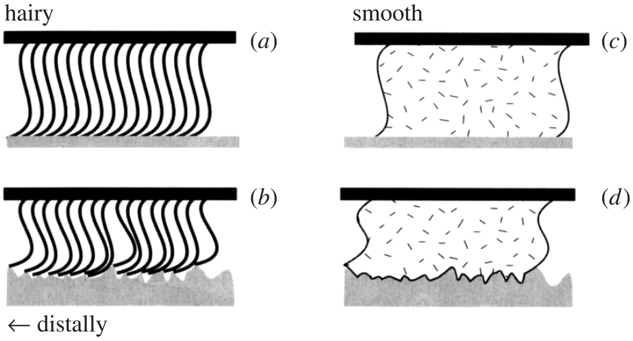

Figure 4. Schematic of action of the (*a*), (*b*) 'hairy' and (*c*), (*d*) smooth pad-attachment systems on (*a*), (*c*) smooth and (*b*), (*d*) structured substrates. Both systems are able to adapt to the surface profile. (Reproduced with permission from Scherge & Gorb (2001).)

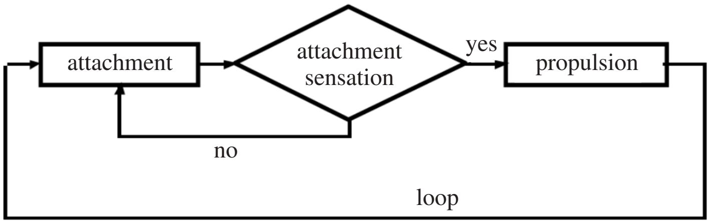

Figure 5. Perception–reaction loop for locomotion.

of surfaces with tribological properties optimized for micromachines navigating the gastrointestinal tract.

An optimized interface (from the morphological point of view) between the locomotion device and the tissue is not sufficient to reproduce an effective biomimetic adhesion and locomotion system. A sort of reactive behaviour, even if at low level, must be implemented in order to obtain a 'bio-attachment' and a 'bio-locomotion'. For example, the simplest inchworm system is based on clamping modules (which attach to the substrate) and elongation modules (which produce a displacement when at least one clamping module is active). The locomotion system of worms is controlled by an action–perception–reaction architecture, which makes the mechanism effective. Not much is known about the low-level control of locomotion in lower animal forms; however, it is based on sense organs (mainly touch receptors) spreading from the *setae* (bristles) that cover the animal body in many worm species (Brusca & Brusca 1990). As illustrated in figure 5, the locomotion unit possesses a low-level control (attachment sensation) that allows activation of the propulsion system only if clamping is effective. Similar architectures drive the behaviour of the arms of the octopus when it clamps to stones using its suckers.

This simple perception–reaction loop is well known and it has been implemented in almost every robotic system and also in several toys mimicking animal behaviours (e.g. Sony's AIBO robotic dog). Most robots with a perception–reaction behaviour exploit a high-level control based on vision sensors. However, some examples exist of artificial creatures with a reaction behaviour depending on 'low-level' stimuli (touch, temperature, etc.) and affecting the 'shape' of the creature itself (e.g. the antenna of snails retract when slightly touched). When working with locomotive micromachines,

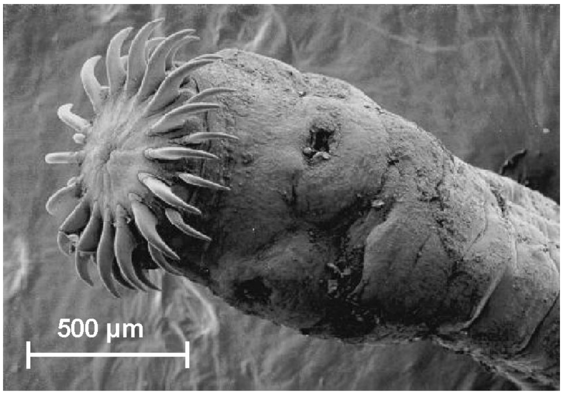

Figure 6. Head of a tapeworm with suckers and hooks.

the main goal and challenge is the implementation of the perception–reaction loop in miniaturized structures. In fact, the classic machine model in which discrete elements (mechanisms, sensors, actuators, control) can be isolated and identified fades out and go towards a (mechatronic) structure embedding and integrating the above subcomponents.

Smart materials (e.g. piezoelectric materials, polyelectrolyte gels, conducting polymers, carbon nanotubes and electrostrictive materials) seem to be suitable for biomimetic applications (Baughman *et al.* 1999). In fact, their low density, their active mechanical characteristics (comparable or higher to those of natural structures, including human structures) and the possibility to drive them by external stimuli fit perfectly with the specifications typical of biomedical microdevices, structures and subsystems with integrated functions.

4. Proposed artificial solution for adhering onto the gastrointestinal tract

On the basis of the analysis of the methods exploited by the living creatures to adhere onto different kinds of tissue, we have identified in *Taenia solium* (tapeworm) an effective mechanism to grasp safely and firmly the intestine wall. The tapeworm head (figure 6) consists of four lateral suckers and a top hooked membrane that can protrude reversibly to grasp the intestinal tissue.

This solution is very effective: the tapeworm can stay attached in the intestine of the host for many months without damaging the tissue and affecting the intestinal peristalsis. In a manner similar to the mechanism of figure 2, suction is used to approach the tissue, but the real grasping function is performed by mechanical structures (the jaws in the colonoscope and the hooks in the tapeworm).

We have designed an artificial device exploiting a similar working principle and are able to replicate the adhesion mechanism of the tapeworm. The system includes a sucker and many microhooks integrated onto an elastic membrane. When the bottom frame moves down, a slight vacuum is generated at the sucker surface and the stretching of the elastic membrane causes the hooks to protrude (figure 7).

In this solution, the same actuation produces a volumetric vacuum and generates the protrusion of the hooks; this feature appears very useful in terms of integration,

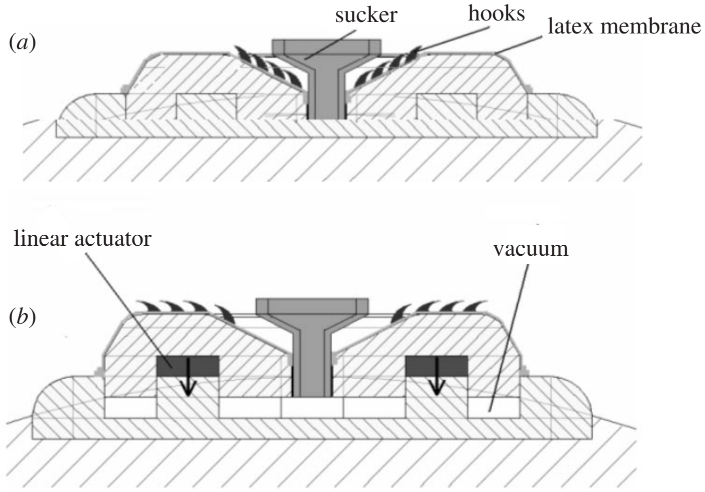

Figure 7. (*a*) Inactive system. (*b*) System that produces the vacuum and protrudes the hooks.

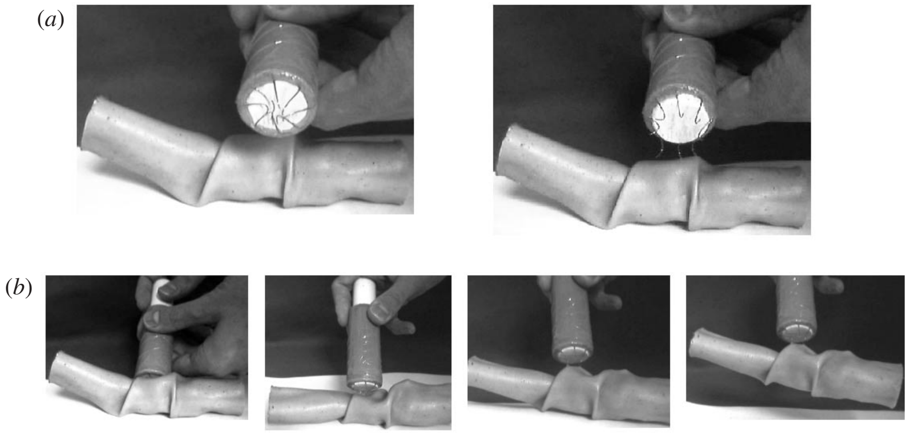

Figure 8. (*a*) The grasping structure in 'close position' and 'open position'.
(*b*) Four phases of the grasping of a colon tissue simulator.

power saving and miniaturization. In case of collapsed tissue (i.e. tissue already covering the structure), the suction function may not be important for the effectiveness of the whole system. We have tested a preliminary prototype (consisting only of a protruding hooked membrane, without suction ability) on a colon-tissue simulator, and they have obtained encouraging tasks in terms of grasping ability, as illustrated in figure 8.

(*a*) *Fabrication of the microhooks*

From a technological point of view, the study and replication of the mechanical structures of parasites for attachment are not trivial. The fabrication of micro-sized biomimetic three-dimensional hooks and grasping microstructures can represent a frontier for modern microfabrication technologies.

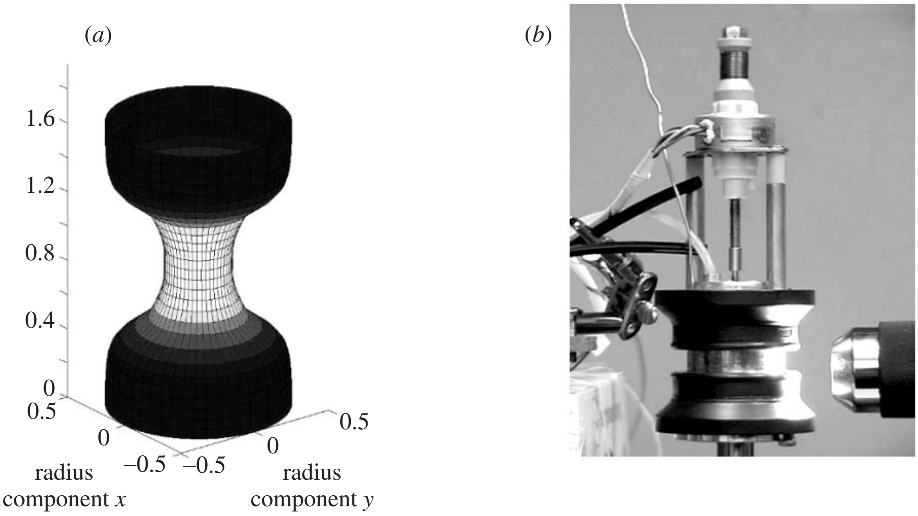

Figure 9. (*a*) Simulation of the behaviour of a melted polymer between two moving supports. (*b*) Laboratory equipment for fabricating the microhooks.

Therefore, the authors designed a process suitable for the fabrication of microhooks with tunable geometric parameters. The method consists of melting a polymer (e.g. nylon, which possesses mechanical features similar to bio-structures) and shaping it by exploiting the surface tension and the viscosity of the material in the liquid phase. A simulation of the process was implemented using the MATLAB software package, as shown in figure 9*a*, and a simple fabrication device was built in order to fabricate the hooks (figure 9*b*). The fabrication device consists of a mobile ring, which is driven by a stepping motor and which pulls a short nylon strip that has been melted in a suitable housing. The melting of the nylon, which happens at *ca.* 237 °C, is produced by a heater and the process is monitored by a fibre-optic microscope. A fresh air supply can be added during the fabrication process in order to enhance the cooling process after the stretching. The data from the motor (speed, stroke, number of steps) and from a thermocouple, which is located very close to the nylon strip, are acquired by the PC. Normally, the stroke ranges between 0.5 and 2 mm and the speed ranges between 0.5 and $3\ \mathrm{mm\,s^{-1}}$.

By tuning the temperature (warming and cooling) and the motor speed, it is possible to fabricate microhooks with the desired profiles. Three phases of a fabrication process are illustrated in figure 10*a*. The first one corresponds to the melting of the polymer, the second one describes the stretching process and the third one illustrates the cooling process of the material in order to fix the desired configuration before the detachment of the two hook ends.

In figure 10*b*, one microfabricated hook is shown and compared to the natural hook of *T. saginata*.

The manufacturing of the hooks, using the method of the liquid bridge, allows adjustment of the shape of the hooks and investigation of the most effective hook shape, but it introduces some important drawbacks: it is a slow process, which is not suitable for a large number of elements; moreover, the process is not easily repeatable (the obtained hooks are different in shape). Once the most suitable hook shape has been identified, the main issue is to replicate it in a batch process.

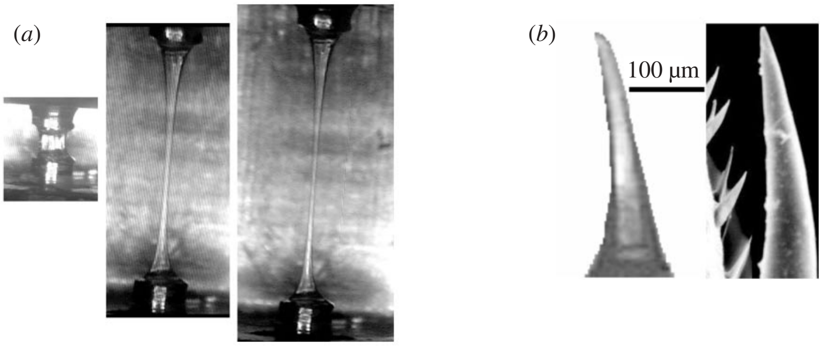

Figure 10. (*a*) Three process steps of a microhook fabrication.
(*b*) Comparison between an artificial hook and a tapeworm hook.

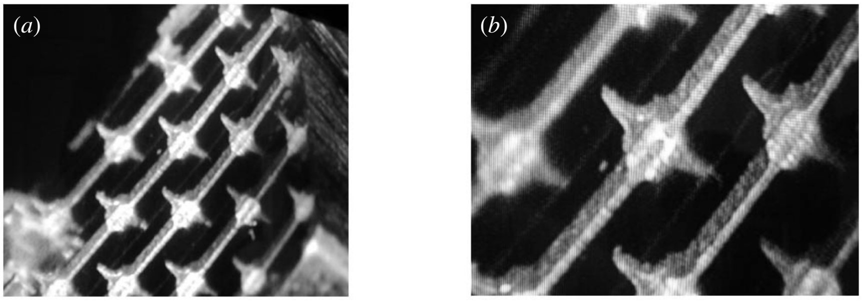

Figure 11. (*a*) Arrays of polymeric microhooks. (*b*) Detail of few microhooks.

We approached this problem by using microelectro-discharge machining (micro-EDM). They designed a set of hooks in a saw-toothed configuration and machined them by micro-EDM in aluminium. They then used this metal structure as a mould for wax by obtaining the negative structure of the original one and they used the wax as a mould for an epoxy resin (EPOTEK 301-2), which was selected as the structural material for the hooks. Figure 11 shows some arrays of microhooks with a height of 300 μm and an average width of 100 μm.

(*b*) *Actuation of the elastic membrane for protruding hooks*

The activation of the hooked membrane according to the scheme of figure 7 requires the exploitation of a linear and compact actuator, ideally actuated by electrical power. With this solution, electrical wires may be substituted by microbatteries in a future version of the device, thus allowing the realization of a wireless system.

Two parallel approaches have been followed in order to actuate an elastic membrane, which will integrate the microhooks in a more advanced version of the device.

The first approach for the membrane actuation consists of exploiting the phase change of a biphasic gas (diethyl ether). An elastic membrane collects 1 ml of ether and it is heated by an electrical resistance to above the transition temperature (34.5 °C); the gas that is generated produces a pressure, inflating the membrane by doubling its volume. The method is fully reversible, although the cooling process is quite long (10–20 s). Improved condensation systems will help to speed up the overall inflation–deflation process. Figure 12 shows two phases of the device actuation.

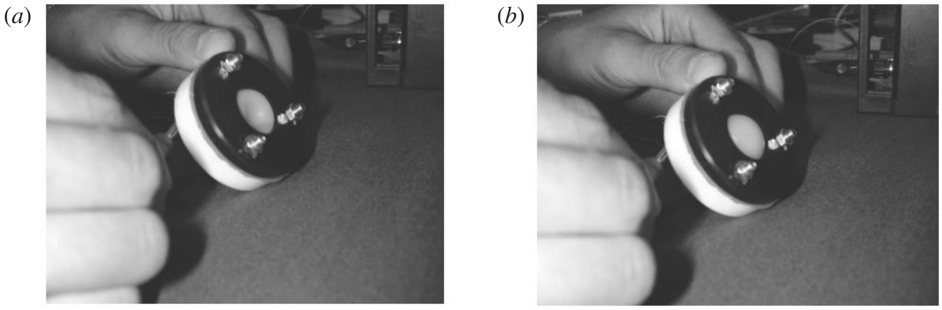

Figure 12. Phase-changing phase device. (*a*) Initial condition. The fluid is in the liquid state. (*b*) Final condition. The evaporation of the biphasic gas inflates the latex membrane.

Figure 13. (*a*) The IPMC hooked membrane actuator. (*b*) Prototype of the actuator without the membrane (maximum positive stroke). (*c*) Prototype of the actuator (minimum negative stroke).

The second approach we followed to design and fabricate an actuation mechanism for the elastic membrane exploits special smart actuators, which are known as ionic polymer–metal composites (IPMCs). These actuators, like many conducting polymer and gels, have the ability to produce large strains by applying low voltages (1–2 V) (Cohen *et al.* 2002). Moreover, some smart polymers exist, which are able to produce effective work when they are triggered by changes in temperature, pH, humidity or other environmental effect. For these reasons, the IPMC actuators look very promising for biomedical applications. Specifically, the authors used commercial IPMC (type MS-417) produced by Biomimetic Products Inc. (Cedar Crest, NM, USA). These polymers can be cut into strips: each can bend at temperatures up to 180 °C and can produce a force that is 10–50 times the weight of the strip itself.

We designed a configuration for the membrane actuator consisting of several IPMC strips in series, which provide a piston with a large stroke (figure 13*a*). The first prototype was fabricated and preliminarily tested as illustrated in figure 13*a*, *b*. When the IPMC-based actuator is active, the piston goes forward and pushes the elastic membrane on the top of the structure, thus causing the protruding of the hooks. In the current version, illustrated in figure 13*c*, *d*, the hooked membrane has not yet been integrated.

5. Conclusions and future work

This paper presents a biomimetic approach to the problem of locomotion in the human body, with particular attention to the gastrointestinal tract. Many biological solutions for locomotion and adhesion on different terrains look very promising, particularly when the traditional design and fabrication rules of mechanical engineering do not achieve the required degree of integration and the appropriate function fusion with the scaling-down of the size of the device.

Starting from the project to replicate the adhesion structure of a tapeworm, which has developed effective mechanisms of grasping the intestinal wall, our main objective was the implementation of an integrated subsystem having a reflexive behaviour, that is, when some responses are directly ‘hardwired’ to external stimuli. Polymeric materials are very promising regarding this possibility; in fact, the reversibility of actuation and ‘sensation’ capabilities makes it possible to develop mechanisms that exhibit an automatic reaction when triggered by certain physical and/or chemical signals. By stressing the preliminary results illustrated in § 4 *b*, we can design an active hooked membrane made of smart polymer sensitive to external signals that are related, for example, to the proximity of the polymer to the substrate to which it has to adhere. If the amplified response to such a signal is to protrude, the structure would merge the sensing and the actuation functions and would constitute a cellular module able to perform reflex reactions. Our future activity will essentially focus on the following aspects.

(i) We seek a better understanding of control strategies of lower animals, and an investigation of the basic principles regulating their sensory feedback in terms of force sensors and touch receptors is needed. The knowledge of touch and force receptors in lower animal forms in the literature is rather vague, and major efforts are necessary to analyse the issue of sensory feedback with a engineering focus. This approach will allow us to overcome the limits of purely micromechanical solutions and to achieve a low level of autonomous control. The advantages in terms of medical applications are straightforward: the physician could just control the medical procedure at high level and he/she could concentrate on the medical diagnosis, allowing the biomimetic device to deal autonomously with the low-level navigation problems. Such a system would exhibit a reflexive behaviour in addition to the ‘pre-planned’ actions, thus producing extraordinary advancements in standard diagnostics and opening possible new frontiers for endoscopy.

(ii) Refinements need to be made to the microfabrication techniques employed up until now in order to make these techniques more flexible to machine and to construct *soft* and *bio-like* materials. There are already a few microfabrication techniques in existence that look promising for realizing structures which have embedded components for mini-scale sensing and actuation (Clark *et al.* 2001). The challenge is to fabricate truly micro-sized structures with high accuracy and flexibility in terms of materials and shapes. When the dimensions are scaled down, the effectiveness of the microstructures depends very much on the geometry and size (e.g. the gecko foot works because its hairs have that specific size; the tapeworm hook is effective and painless because it is very thin).

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References

Autumn, K., Liang, Y., Hsieh, T., Zesch, W., Chan, W. P., Kenny, T., Fearing, R. & Full, R. J. 2000 Adhesive force of a single gecko foot-hair. *Nature* **405**, 681–685.

Baader, A. P. 1997 Interneuronal and motor patterns during crawling behaviour of semi-intact leeches. *J. Exp. Biol.* **200**, 1369–1381.

Baughman, R. H. (and 12 others) 1999 Carbon nanotube actuators. *Science* **284**, 1340–1344.

Brusca, R. C. & Brusca, G. J. 1990 *Invertebrates.* Sunderland: Sinauer Associates.

Clark, J. E., Cham, J. G., Bailey, S. A., Froehlich, E. M., Nahata, P. K., Full, R. J. & Cutkosky, M. R. 2001 Biomimetic design and fabrication of a hexapedal running robot. In *Proc. IEEE Int. Conf. on Robotics and Automation, 21–26 May 2001, Seoul, Korea*, vol. 4, pp. 3643–3649. New York: IEEE Press.

Cohen, Y., Bao, X., Sherrit, S. & Lih, S. S. 2002 Characterization of the electromechanical properties of ionomeric polymer–metal composites. In *Proc. of SPIE Smart Structures Materials Symp., NDE Conference, San Diego, CA, 18–20 March 2002*, pp. 219–238. Bellingham, WA: SPIE.

Cotton, P. B. & Williams, C. B. 1990 *Practical gastrointestinal endoscopy.* Oxford: Blackwell.

Dario, P., Carrozza, M. C. & Pietrabissa, A. 1999 Development and in vitro tests of a miniature robotic system for computer-assisted colonoscopy. *J. Comput. Aided Surgery* **4**, 4–14.

Dickinson, M. H., Farley, C. T., Full, R. J., Koehl, M. A., Kram, R. & Lehman, S. 2000 How animals move: an integrative view. *Science* **288**, 100–106.

Hirose, S., Cave, P. & Goulden, C. 1993 *Biologically inspired robots: snake-like locomotors and manipulators.* Oxford University Press.

Miller, B. A., Kolonel, L. N., Bernstein, L., Young Jr, J. L., Swanson, G. M., West, D., Key, C. R., Liff, J. M., Glover, C. S. & Alexander, G. 1996 Racial/ethnic patterns of cancer in the United States 1988–1992. NIH Pub. no. 96-4104, National Cancer Institute, Bethesda, MD.

Phee, S. J., Ng, W. S., Chen, I. M. & Seow-Choen, F. 1997 Development of new locomotive concepts to be used in automation of colonoscopy. In *Proc. 9th Int. Conf. for Biomedical Engineering, Singapore*, pp. 87–92. New York: IEEE Press.

Phee, L., Accoto, D., Menciassi, A., Stefanini, C., Carrozza, M. C. & Dario, P. 2002*a* Analysis and development of locomotion devices for the gastrointestinal tract. *IEEE Trans. Biomed. Engng* **49**, 613–616.

Phee, L., Menciassi, A., Gorini, S., Pernorio, G., Arena, A. & Dario, P. 2002*b* An innovative locomotion principle for minirobots moving in the gastrointestinal tract. In *Proc. IEEE Int. Conf. on Robotics and Automation, Washington, DC*, vol. 2, pp. 1125–1130. New York: IEEE Press.

Scherge, M. & Gorb, S. N. 2000 Using biological principles to design MEMS. *J. Micromech. Microengng* **10**, 359–364.

Scherge, M. & Gorb, S. 2001 *Biological micro- and nanotribology: nature’s solutions.* Springer.

Skierczynki, B. A., Wilson, R. J. A., Kristan, W. B. & Skalak, R. 1996 A model of the hydrostatic skeleton of the leech. *J. Theor. Biol.* **181**, 329–342.

Treat, M. R. & Trimmer, W. S. 1997 Self-propelled endoscope using pressure-driven linear actuators. United States Patent no. 5595565.