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ORIGINAL ARTICLE

Soft Robotics Technologies to Address Shortcomings in Today's Minimally Invasive Surgery: The STIFF-FLOP Approach

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Abstract

Most devices for single-site or natural orifice transluminal surgery are very application specific and, hence, capable of effectively carrying out specific surgical tasks only. However, most of these instruments are rigid, lack a sufficient number of degrees of freedom (DOFs), and/or are incapable of modifying their mechanical properties based on the tasks to be performed. The current philosophy in commercial instrument design is mainly focused on creating minimally invasive surgical systems using rigid tools equipped with dexterous tips. Only few research efforts are aimed at developing flexible surgical systems, with many DOFs or even continuum kinematics. The authors propose a radical change in surgical instrument design: away from rigid tools toward a new concept of soft and stiffness-controllable instruments. Inspired by biology, we envision creating such soft and stiffness-controllable medical devices using the octopus as a model. The octopus presents all the capabilities requested and can be viewed as a precious source of inspiration. Several soft technologies are suitable for meeting the aforementioned capabilities, and in this article a brief review of the most promising ones is presented. Then we illustrate how specific technologies can be applied in the design of a novel manipulator for flexible surgery by discussing its potential and by presenting feasibility tests of a prototype responding to this new design philosophy. Our aim is to investigate the feasibility of applying these technologies in the field of minimally invasive surgery and at the same time to stimulate the creativeness of others who could take the proposed concepts further to achieve novel solutions and generate specific application scenarios for the devised technologies.

Introduction

The advantages of minimally invasive surgery (MIS), single-port interventions, and natural orifices transluminal surgery (NOTES) are universally recognized and include reduced patient trauma, shortened hospitalization, and improved patient recovery.[1] However, the intrinsic difficulties of operating remotely, through small incisions and with instruments whose distal maneuverability is extremely limited, are far from being solved. Current laparoscopic instruments have been developed by different companies and research groups and fall broadly into three main categories: (1) instruments with articulated tips,[2–5] (2) tools that enter through small channels and are internally deployed for accessing a larger workspace,[6] and (3) robotic handheld tools.[7,8] It is noticeable that virtually all of today's instruments make use of traditional design solutions based on cables, pulleys, and gear systems.

Most devices—including those that are still in the research phase—are very application specific and, thus, capable of effectively carrying out specific surgical tasks only. However, most of these instruments are rigid, lack a sufficient number of degrees of freedom (DOFs), and/or are incapable of modifying their mechanical properties based on the tasks to be performed.[9] The current philosophy in instrument design is mainly focused on creating minimally invasive

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surgical systems using rigid tools equipped with dexterous tips. Only few research efforts are aimed at developing flexible surgical systems, with many DOFs or even continuum kinematics. The creation of soft and shrinkable instruments for self-propulsion in diagnosis and for basic surgical applications has been proposed for the gastrointestinal track in refs.[10,11] Despite this, the replication of this approach for devising novel surgical instruments has only been attempted in the framework of the ongoing EU project Stiffness Controllable Flexible & Learnable Manipulator for Surgical Operations (STIFF-FLOP).[12]

Being inspired by biology, we envision creating such soft and stiffness-controllable medical devices using the octopus as a model. The octopus presents all the capabilities requested and can be viewed as a precious source of inspiration. It completely lacks rigid structures and this enables the possibility to squeeze its body to pass through very narrow apertures. But at the same time it shows very advanced manipulation capabilities like arm elongation, bending, and stiffening thanks to its peculiar muscular arrangement. These capabilities are all desirable in a surgical manipulator and, above all, if connected with the same intrinsic softness that can be found in the octopus. The concept of taking inspiration from nature to improve technology is not new: in particular, cephalopods have been studied by many scientists and engineers for the development of new soft robots.[13–15] Similarly, elephant trunks were used for inspiring a soft manipulator for industrial applications.[16] Mimicking animals requires investigating the most suitable technological solutions, and often new hardware and software approaches have to be developed too, such as new materials, mechanisms, sensors, actuators, and control schemes.

Currently, flexible surgical systems aim mainly at reaching remote body areas exploiting their highly dexterous structure, thus enabling the possibility to perform a large number of procedures from a minimally invasive access.[17] Such systems are based on mechanisms composed of rigid components that are not specifically designed to interact with the surrounding biological structures. On the other hand, soft robotics can provide the tools to develop a robot that can equally reach remote areas of the body and possibly actively and safely interact with the environment thanks to its controlled compliance. In the following sections, we will illustrate the candidate technologies that can be applied in the design of such a novel manipulator for flexible surgery by discussing their potential and by presenting feasibility tests of novel prototypes responding to this new design philosophy.

A Novel Surgical Manipulator

The envisaged manipulator for keyhole surgery should be thin, flexible, or even soft; have multiple DOFs distributed along its length, with the possibility of elongating for reaching remote areas of the workspace; and also able to be squeezed so that it can advance into narrow and commonly hard-to-access areas. In addition, with the requirement of a solid platform for precise intervention, the surgical manipulator should also be able to stiffen entirely or partially, on demand and as required by the operator. Selective stiffening of different sections along the surgical arm is expected to lead to increased navigation and disturbance rejection capabilities for better target reaching and would allow tuning its compliance in response to the surroundings.

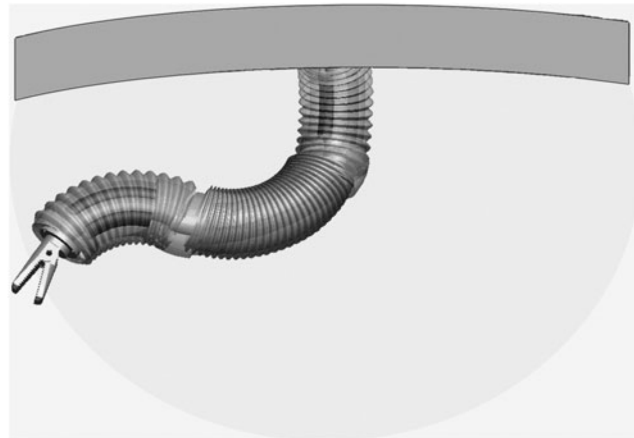

FIG. 1. Concept design of the modular surgical manipulator.

To visualize the envisaged STIFF-FLOP arm, a concept drawing is provided in Figure 1. A modular structure is proposed: each module is able to provide all the functionalities in terms of movements and stiffening capabilities and complex behaviors can be obtained by composing multimodule structures.

The expected advantage of such a soft modular structure is the possibility to actively and safely interact with the surgical environment. The envisaged manipulator will be able to apply forces in specific sections of its body: this would allow holding, for example, an organ with the proximal module and to use the distal one to perform a delicate surgical task. The retraction of organs in order to create space for the operation through other instruments is particularly challenging in single-access procedures, because the surgical target is typically located far from the insertion point and applying large forces/torques can be complex.[9,18] The main functions that should be considered for selecting the candidate technologies for the proposed manipulator are the following: (1) the ability to squeeze actively through a narrow opening and to be squeezed passively by external forces without being damaged and by keeping its intended functionalities; (2) the ability of omnidirectional multibending; and (3) the ability to modulate arm stiffness. The main technological bottleneck behind these requests is actuation. The following sections will critically examine the candidate technologies for fulfilling these requirements. It should be kept in mind that the ability to squeeze is something that cannot be found in traditional, robotic surgical tools and produces severe constraints in terms of material selection.

How to Achieve Soft Multibending and Elongation?

Despite the many benefits of traditional surgical approaches, clinicians agree on the significant drawbacks still associated with MIS, including difficulties and limitations in instrument control and ergonomics caused by the rigid instrumentation and the fulcrum effect produced by operating with those rigid tools through spatially fixed trocar ports.[19] From a robotic viewpoint, a deep analysis of the most advanced robotic platforms in the surgical landscape reveals a strong need for special instruments with high flexibility, stability, and dexterity to reach operation target sites through complex anatomical pathways.[17] In this sense, the main limitation in satisfying this need is represented by the immaturity of new actuation technologies currently emerging in robotics research labs to represent a valid and practical alternative to classical motor-based approaches.

A new emerging class of technologies that already demonstrated their potential to fill the gap between natural and artificial muscles is represented by electroactive polymers (EAPs).[20] They are mainly based on elastomeric polymers and are activated by electric stimuli, which cause a size and shape variation through electronic or ionic mechanisms.[21] In general, they have a power density similar to natural muscles, and they can be easily scaled in whatever shape. However, currently they have limited applicability because of the high electric fields required (in the case of electronic EAP) or the slow response and low lifetime (for the ionic EAP). Among shape-memory materials, shape-memory alloys (SMAs) overcome both these issues: a reasonable response speed can be achieved accompanied by a low activation voltage (although, high currents are still needed). These metal alloys are capable of undergoing a certain strain and subsequently recovering to their original shape when heated.[22] SMAs allow creating robotic systems that are drastically small in size, weight, and complexity, when compared with traditional robots. In fact, their large force–weight ratio, limited volume, inherent sensing capability, and noise-free operation enable the employment of this technology in soft robotics.[23] Unfortunately, SMAs have drawbacks too: the heating is often provided through the supply of relative high currents and the activation temperature is generally not compatible with surgical procedures. An interesting alternative to the metal alloys, which also belong to the class of shape-memory materials, is shape-memory polymers (SMPs), which exploit the same principle as SMAs, but the recovery can be triggered by various external stimuli such as light, electric current, magnetic field, or chemical parameters. They have drawn considerable research interest in the last few years because of their use as actuators in biomedical devices. In several fields of applications, SMP materials have been proved to be suitable substitutes to metallic ones because of their higher flexibility, biocompatibility, and wide range of shape modifications at a lower cost. Although many researchers have focused their efforts on stimuli-responsive SMPs and their composites, no solid and reliable results have been achieved yet.[24]

Fluidic actuators could represent a different, yet effective, solution especially if combined with specific manufacturing processes for soft devices. Flexible fluidic actuator is a term used for a wide range of actuation systems, but generically these systems present a combination of a flexible structure with a fluidic actuation that brings peculiar advantages such as the absence of friction and leakages (unlike piston-based actuator) during the actuation. The most exploited configuration has expandable chambers built in the flexible structure that can change their volume if a pressurized fluid is supplied.[25] The change in volume is then converted into the movement of the structure connected to the inflatable chamber. If applied in a cylindrical armlike robotic system, fluidic actuators are able to adapt and transform the force because of fluid pressure against the inner chamber walls into a traction force or a bending movement of the arm itself.[26] A recent review on these mechanisms can be found in ref.[27] The main disadvantages of fluidic systems are the risk of leakages or—even worst—the possibility of burst of the inflated chambers. In the medical field, such issues can be addressed by keeping the pressures low and in a safe region. The actuating pressure can be constrained under a safe limit that prevents internal organs or tissue damages in case of bursting. To further enhance the safety level in the case of internal chamber bursting, an outer sheath can be arranged around the manipulator body, thus containing the possible damages caused by the burst of an inflated chamber. The employment of biocompatible fluids rather than gases would be also a valuable option for actuation as an additional safety factor in the case of fluid losses.

All technologies mentioned above, if properly integrated in an actuation system, can be used to enable bending and elongation in a soft manipulator, and to some extent they can maintain the squeezability of the system. To properly deal with the choice of the actuation method, a qualitative direct performance comparison has been conducted among the aforementioned soft technologies. The classification is reported in Table 1; for the sake of completeness, also the traditional approaches employing motors and cables have been included. The results of the comparison reported in Table 1, alongside considerations about limitations and current constraints concerning available technology and fabrication methods, highlight the use of flexible fluidic actuators as one of the most appropriate solutions to meet the specific requirements.

How to Realize Selective Stiffening?

Stiffness variation is one of the main features of the proposed STIFF-FLOP arm. The arm should be able to safely interact with the surgical environment, adapting its stiffness according to the organs and the surgical procedure. Indeed, the arm should be able to navigate in the body cavities in a floppy state and then selectively stiffen some of its segments to actively interact with organs or accomplish specific surgical tasks. Flexible endoscopes are being used for NOTES or laparoendoscopic single site (LESS); these instruments are used because of their high flexibility, but they may lack stability that rigid tools provide and that is required for certain procedures.[9]

In general, flexible systems typically have a flexible ''backbone'' or a spring spine,[14,28] and are actuated by motors located externally. The flexible backbone gives them low stiffness, thus making it difficult to control the rigidity. The majority of continuum-like robots are based on cable actuation; in these cases, stiffness can be tuned by tensioning all the cables along the robot at the same time.[29] However, such a strategy has an intrinsic drawback; for instance, it will never be possible to stiffen only the middle part of the robot while keeping floppy the distal and the proximal ends. This particular feature can be useful for exploiting at the best of its potential the envisaged STIFF-FLOP manipulator. In the scenario where the manipulator performs different actions with the different modules composing it, the combination of actuation and stiffness of the single modules is of outmost importance. As an example, we can figure out the case of a three-module manipulator where the first module (proximal) provides the first orientation of the arm, and the second shifts an organ to create the necessary space for the third module to reach the surgical target where performing the task onto. In this configuration, the middle module can adapt its stiffness to the organ in order to lift it effectively.

Finally, in cannula robots that are based on telescopic motion of precurved superelastic tubes sliding onto each

Table 1. Comparison Table of Several Candidate Technologies to Obtain Soft Multibending and Elongation

Actuation technology			*Physical phenomenon*	*Scaling of dimensions*	*Strain*	*Stress*	*Power density*	*Response velocity*
Motor-driven solutions	Electromagnetism		Electromagnetic motors pulling cables fixed at distal points along the structure	Low, mainly because of the motors and cable mechanisms	High	Medium/low	Medium	High
SMA	Temperature change		Thermal-driven change of crystalline structure leading to a shape change	High	Wires: very low Springs: high	Wires: high Springs: medium/low	High	Medium/low
SMP	Light, electric current, magnetic field, chemical stimuli		Light, electric current, magnetic field, or chemical stimuli can change polymer chain structure leading to a shape change.	High	Medium	Medium	Medium/low	Low
EAP	Electric field	Electrons	The application of an electrical potential difference leads to electrostatic interactions generating internal stresses and deformations.	Medium/high	Medium/high	Medium	Medium/low	High
		Ions	The application of an electrical potential difference leads to ions migration causing deformations.	Medium/high	Axial: low Bending: medium/high	Medium/low	Medium/low	Low
Flexible fluidic actuators	Pressurized fluids	Liquids (hydraulic)	Pressurized liquid to change elastomeric chambers volume converted into specific movements	Medium/low, mainly because of the hydraulic pumps	High	High	High	Medium/high
		Gases (pneumatic)	Pressurized gas to change elastomeric chambers volume converted into specific movements	Medium, mainly because of the pneumatic pumps	High	Medium	Medium/high	High

EAP, electroactive polymer; SMA, shape-memory alloy; SMP, shape-memory polymer.

Table 2. Comparison Table of Several Candidate Technologies for the Variation of the Stiffness

Stiffening strategy	*Physical phenomenon*	*Controllability*	*Response velocity*	*Stiffening range*
Material stiffening				
Phase change of thermoplastic polymers	Phase change of thermoplastic polymers with temperature	Low	Seconds	From values resembling low-viscosity fluids to values resembling rigid nylon
Magnetorheology	Change their viscosity in response to magnetic fields	Low (difficult to tune stiffness)	Milliseconds	Yielding strength of 100 kPa (239 kA/m magnetic field)
Electrorheology	Change their viscosity in response to electric fields	Low (difficult to tune stiffness)	Milliseconds	Yielding strength from 0 to about 5 kPa (5,000 V/mm at 2–15 mA/cm^2)
Structural stiffening				
Locking of relative motion between two or more subsequent components of the structure	Friction between two following joints (in case of a backbone structure) or between the outer edges of elements in contact with each other, because of the tensioning of the structure	Low, mainly on–off	High (dependent on the actuation technology, e.g., motors for tensioning cables)	Shapelocking capabilities applying high tensioning forces
Jamming-based stiffening of the structure	Interparticle friction caused by density increase in a vacuumed flexible membrane embedded in the structure (granular jamming) Increase in friction caused by vacuum between concentric hollow cylinders along the structure (layer jamming).	Possible, by controlling the vacuum level	High (mainly depending on the vacuuming system)	High deformability in the fluid state, and drastic stiffness increase in the solid state, without significant change in volume

other,[30,31] the tuning of the stiffness is realized through control,[32] by implementing a stiffness controller based on a modified position controller for obtaining a user-defined stiffness at the tip of the manipulator.

Following the approach described in ref.,[9] different stiffening mechanisms were considered for the STIFF-FLOP modular arm. Rigidity control based on material stiffening and structural stiffening has been evaluated and reviewed, as summarized in Table 2. Material stiffening involves the use of materials that can undergo stiffness variations because of the applied physical stimuli. Phase change polymers have been used for stiffness variation in refs.,[33–38] and phase change metals were proposed in ref.[39] Magnetoreological fluids and electrorheological fluids were proposed in refs.[40,41] In the case of structural stiffening, the structure is changed, for example, by fixing the relative motion between the components of a system as in refs.[42–44] A different example of structural stiffening is represented by jamming. In this case, stiffness variation can be obtained by increasing the friction between a number of layers of material (layer jamming)[45] or between granular particles (granular jamming).[46]

Given the specific requirements and features of the STIFF-FLOP arm, the chosen strategy is based on the physical phenomenon of granular jamming. As stated in ref.,[46] jamming is a phenomenon where a sort of phase change of the granular matter occurs because of external stimuli. Such variation in the mechanical properties that granular matter experiences can be obtained by temperature changes, shear stress, or an increase of the density of the system (i.e., compacting the granules). In robotic applications, jamming is

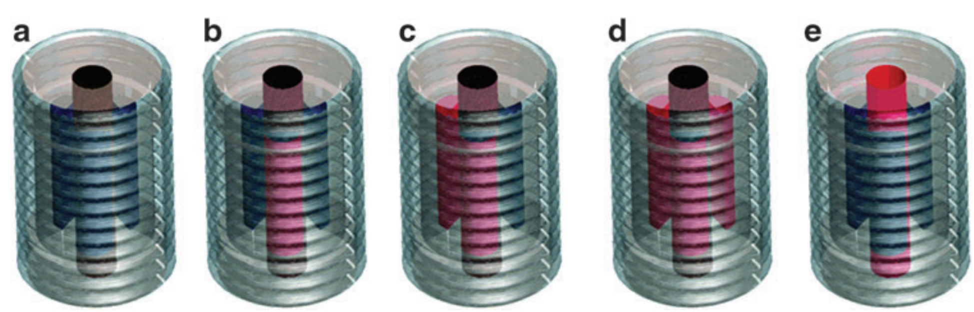

FIG. 2. Structure of the STIFF-FLOP module by highlighting in red the different possible chamber activation **(a–e)**. STIFF-FLOP, Stiffness Controllable Flexible & Learnable Manipulator for Surgical Operations. Color images available online at www.liebertpub.com/soro

Table 3. Dimensions of the Single Module (All the Values Are Expressed in Millimeters)

Module length	*Fluidic chamber length*	*Fluidic chamber diameter (half circle)*	*Stiffening chamber diameter*	*Diameter of the silicone body*	*Diameter of the module (with crimped sheath)*
50	30	8	8	25	32

typically induced by increasing density when a flexible membrane containing granular matter is vacuumed. Density can be controlled by regulating the vacuum level; thus, it is possible to let the particles behave as if they were a liquid, a solid, or something in between. A granular jamming-based stiffening mechanism was selected because it presents the desired property to conform to high deformable structures since its shape, in the not jammed configuration, is mainly because of the properties of the containing membrane. Thus, it can be easily integrated in soft structures and undergo shape modifications. It is worth mentioning that such shape modification may alter the mechanical properties of the stiffening chamber but, although with different efficiency, it will still provide a change in the stiffness properties. In addition, granular jamming-based stiffening mechanisms provide variable stiffness range, fast activation, easy fabrication, and typically limited production costs. Because of this unique feature, many groups have integrated granular jamming into medical and robotic devices such as robotic grippers,[47] tendon-driven manipulators,[48] jamming skin-enabled locomotion robots,[49] variable stiffness endoscopes,[50] emergency vacuum splints,[51] and variable stiffness joints.[52]

Steps Toward Novel Surgical Manipulators

Among the suitable technologies detailed in the previous sections, a very promising combination is represented by the use of fluidic or pneumatic actuation for obtaining multi-bending and elongation, and granular jamming for varying the stiffness: the flexibility of fluidic chambers enables the possibility to bend the manipulator in each direction, while the granular jamming-based mechanism allows the transition from completely floppy and highly squeezable to stiff structures, which are able to produce relatively high forces.

In the design shown in Figure 2a, three fluidic chambers equally spaced in a radial arrangement are embedded in an elastomeric cylinder. The cylinder is surrounded by a crimped sheath that limits the radial expansion of the chamber when inflated with a fluid enabling an effective and controllable motion of the actuator. The relevant dimensions of a single module are presented in Table 3. The current dimensions of the manipulator module are not optimized for specific applications in MIS or NOTES. However, by exploiting the squeezing capabilities, the module diameter could reduce, thus fitting different size access. In this framework, the current work is a proof of concept and aims at evaluating the capabilities of the selected technologies for surgical applications; at this stage, the optimization of the dimensions on a specific surgical procedure is out of the scope of the article.

Exploiting the three fluidic chambers, the actuator is able to perform different motions by changing the pressure in all the three chambers. For example, the actuation of only one chamber (Fig. 2b) results in a bending as demonstrated in Figure 3c. On the other hand, if two chambers are actuated at the same time (Fig. 2c), the bending is in the plane between the two chambers and bigger radius of curvature can be obtained as shown in Figure 3d. The limit case is when all the three chambers are actuated at the same time (Fig. 2d), and in this case we obtain theoretically a pure elongation of the module as in Figure 3b. In Figure 2e the activation of the central stiffening chamber is shown. The stiffening chamber is composed of a latex membrane filled with coffee powder and inserted in an

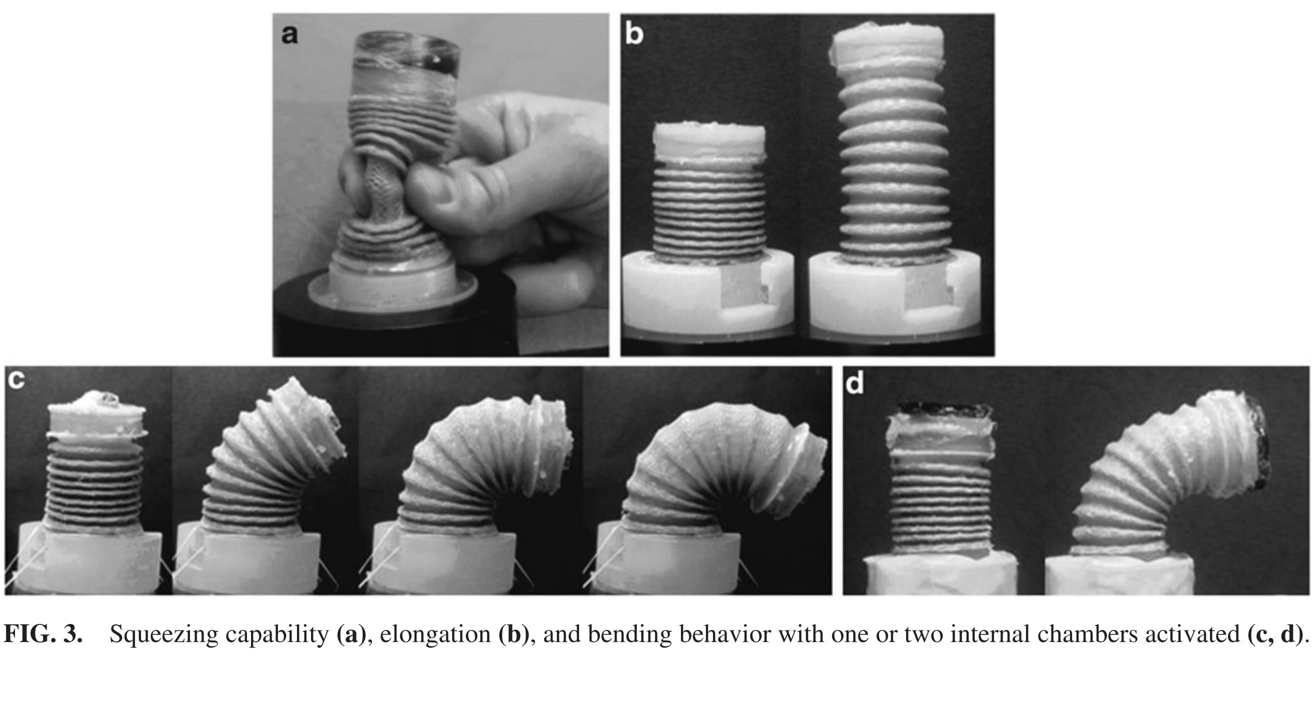

FIG. 3. Squeezing capability **(a)**, elongation **(b)**, and bending behavior with one or two internal chambers activated **(c, d)**.

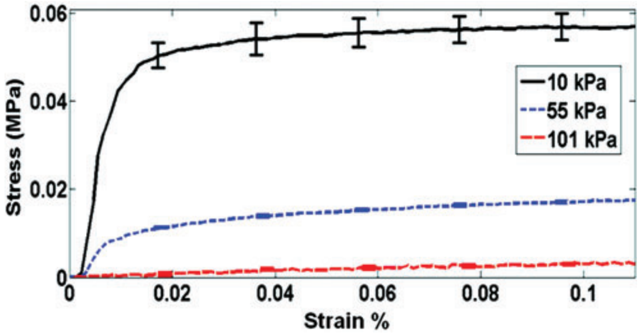

FIG. 4. Stress–strain curves for the stiffening chamber at three different vacuum levels. The curves are the result of 5 tests on a chamber of 8 mm in diameter and 50 mm in length filled with 5 g of coffee. Color images available online at www.liebertpub.com/soro

8 mm channel in the center of the STIFF-FLOP module. Coffee powder was used for the feasibility study since it has been demonstrated in previous studies to perform well as a granular material.[47] In this case, jamming is induced by increasing density in the flexible membrane because of the applied vacuum. By controlling the vacuum level, the stiffness can be tuned. In Figure 4 the stress–strain results on the stiffening chamber at different vacuum levels (from vacuum of 10 kPa to atmospheric pressure of 101 kPa) are reported. As evident from the figure it is possible to obtain a relevant increase in the stiffness level because of the application of vacuum. It is interesting to observe that the sample at atmospheric pressure presents a very low stiffness (0.22 MPa), which is less than for the silicone composing the actuator (Silicone 0050, Ecoflex; Smooth on Inc.; shore hardness = 00–50, 100% tensile modulus = 83 kPa), thus reducing the possible hampering of the active bending of the entire STIFF-FLOP module.

In order to achieve the capability of local activation of the system and to obtain different behaviors along the manipulator, a modular approach has been pursued. The final number of modules composing the manipulator will be mainly a function of the required length and dexterity for a certain medical procedure such as minimally invasive procedures in the abdomen; also, the required capability of the manipulator to navigate around organs in order to reach a target will impact on the number of modules needed. Each module would independently be capable of omnidirectional bending, elongation, and tunable stiffening, thus producing an extended, multi DoF arm with enhanced kinematics and structural properties.

In this framework, the choice of the materials is fundamental and intrinsically connected to the performance of the device. Soft elastomeric materials are necessary to maintain a high degree of squeezability (Fig. 2a) and allow hosting internal chambers for fluidic actuation and channels for granular materials. An additional external structure and a fine-tuning among the geometric parameters are necessary to optimize the efficiency of the modules: the arrangement and shape of the fluidic chambers should maximize the elongation (Fig. 2b) and bending capability (Fig. 2c and d), while the stiffening channel should be dimensioned on the basis of what stiffening range is required. Other details on materials used and fabrication process can be found in ref.[53]

As an example, in Table 4, the main achievable performances of the module showed in Figure 4 are reported.

Table 4. Single-Module Performance

Max bending angle (one chamber @0.65 bar)	120°
Max bending angle (two chambers @0.65 bar)	80°
Max elongation (@0.65 bar)	86.3%
Max force (one chamber @0.65 bar)	24.6 N
Max force (three chambers @0.65 bar, isometric conditions)	47.1 N
Max stiffness variation (@base condition)	46%
Squeezing capability (diameter reduction)	40%

Bending and elongation values were obtained by tracking the tip of the device during the inflation of the fluidic chambers. The force developed by the STIFF-FLOP module was measured by actuating the device in isometric conditions and putting on top of it a load cell for recording the developed force. The stiffness variation was evaluated by imposing a known displacement of the tip of the device and measuring the difference in the force need with and without the activation of the stiffening mechanism. Further characterizations of the module have been reported in ref.[53] Kinematics and dynamic modeling of the system can be approached following the method proposed in refs.[54,55] On the other hand, several improvements and adaptations are needed for control purposes and this topic will be object of future investigations.

As shown in Table 5, the proposed technologies allowed obtaining interesting performances, especially in terms of dexterity and force. Forces obtained, although measured in isometric conditions, indicate that it could be possible to

Table 5. Comparison Between Biological Aspects and Robotic Realization

Key biological inspiration	*Robotic realization*
Octopus arm entirely lacks of rigid structures.	The materials used in the robotic arm present very high compliance since only soft and flexible materials are being used.
Octopus can easily squeeze its body to pass into small apertures.	The manipulator presents high capability to be squeezed to enter through narrow entry points.
The octopus is able to elongate, to stiffen, and to bend its arms in any direction by combining the activation of different muscles.	Every segment of the arm is equipped with different actuation systems that can locally generate elongation, stiffening, and bending in every direction.
Stiffening is done by co-contracting the radial and longitudinal muscles. The radial expansion is constrained by strong radial connective tissue.	The pressure control in hydraulic channels is functionally similar to co-contraction of muscles, while the bendable membrane with its high stiffness in radial direction is functionally similar to the connecting tissue in the octopus limbs. This stiffening mechanism is supplemented by a granular jammed spine in the central axis of the manipulator.

FIG. 5. The current version of the STIFF-FLOP manipulator with two independently controllable soft modules. On the left the overall platform is shown. The central and left images show the manipulator inside the phantom; the picture on the left is the view from a laparoscope.

successfully use the segment for surgical retraction tasks. Indeed, typical retraction tasks require forces between 0.9 and 3.3 N for NOTES procedures[18] or higher in case of more standard procedures where, for example, lifting of an organ such as the liver (normally weighs 1.44–1.66 kg) is required.[56] The stiffness variation is significant when no chamber inflation is performed; the global Young modulus of the system, measured from a deflection test, changes from 1.04 to 1.52 MPa when the stiffening chamber is activated. A preliminary investigation of the stiffening capabilities of the STIFF-FLOP module in different configurations can be found in ref.[53]

As stated in the previous sections, biological octopus models have been taken into consideration as a source of functional inspiration and some key features of the octopus arm have been reproduced in the design in order to integrate such abilities in the STIFF-FLOP arm. In Table 5 a summary of the key functionalities taken from the biological counterpart is reported.

Conclusions

Soft robotics can provide useful tools for the development of innovative devices that can overcome the limitations in current surgical instrumentations. In this article we present an overview of the suitable technologies that can be used in the development of an innovative surgical robot with the abilities of stiffening, elongation, and bending. Fluidic actuation is proposed since it provides high mobility (omnidirectional bending as well as elongation) and a compliant interaction with the surgical environment, thanks to the use of elastomeric materials whose usage further underlines the inherent safety of the device. The proposed design showed promising performances at relatively low fluid pressures.

A stiffening mechanism based of the phenomenon granular jamming is proposed in combination with the flexible fluidic actuator. This mechanism demonstrates a high potential since it is able to adapt to all possible shapes of the actuator and allows changing the stiffness. In this way, it is possible to tune the behavior of the arm when in contact with the environment, from a more compliant interaction to a stiffer interaction, for example, in the case we want to apply specific forces on a target. In a multisegment manipulator architecture like the one presented here, the possibility to combine high dexterity with selective stiffening of some segments allows using the same arm for performing multiple tasks, such as the retraction of an organ with part of the arm stiffened while operating behind the same organ with another distal segment.

In Figure 5 a possible surgical scenario involving a two-module manipulator is shown. The base of the manipulator was connected to a robot arm (Powerball Lightweight Arm LWA 4P; Schunk), which was used for introducing the manipulator inside a phantom through a single incision. In addition, it provides a stable and precise positioning of the base of the STIFF-FLOP manipulator, while this latter is used inside the phantom, showing its flexibility and dexterity.

From a medical standpoint, despite recent comparative trials demonstrating the equivalence of single-port surgery to traditional laparoscopy or multiport robotics for procedures such as nephroureterectomy,[57] it is evident that LESS surgery (and even more so NOTES) based on current technologies remains challenging. It usually takes longer, causes greater surgical fatigue, and is less ergonomic. Biologically inspired robotics is attempting to make life easier for both the surgeon and patient. Rather than crowding multiple stiff or semirigid instruments through a single site, in this work we propose an effective design of a modular stiffness-controllable manipulator that exploits soft robotics technologies to enhance surgical dexterity aiming to achieve difficult tasks, such as precise cutting and suturing in a minimally invasive fashion. The choice of the most suitable technologies took into consideration specific safety issues (in terms of compliance of materials, power supply, and biological hazard) and necessary throughputs (in terms of forces, dexterity, and stiffening capability). The cylindrical and modular design also incorporates hollow lumens that extend from the base to the tip of the arm, providing space for instrumentation and sensors.[58,59] The reported analysis provides a wider overview that can be useful for designing surgical systems with different specific aims. This set of soft technologies can also pave the way to innovative solutions to *feel* and *perceive* surgical tasks and to novel methods for approaching hard-to-reach areas of the abdominal cavity, which nowadays are only reachable by invasive and multiple-port approaches.

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Author Disclosure Statement

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