INVITED PAPER

Soft Robot-Assisted Minimally Invasive Surgery and Interventions: Advances and Outlook

This article provides an in-depth overview of recent progress in soft robotics for surgery and outlines remaining challenges in the development of soft robotics technologies for in-body operation, such as materials selection, tunable stiffness, soft design paradigms, and control issues.

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ABSTRACT | Since the emergence of soft robotics around two decades ago, research interest in the field has escalated at a pace. It is fuelled by the industry's appreciation of the wide range of soft materials available that can be used to create highly dexterous robots with adaptability characteristics far beyond that which can be achieved with rigid component devices. The ability, inherent in soft robots, to compliantly adapt to the environment, has significantly sparked interest from the surgical robotics community. This article provides an in-depth overview of recent progress and outlines the remaining challenges in the development of soft robotics for minimally invasive surgery.

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I. INTRODUCTION

It was the development of the da Vinci system, at the turn of the millennium, which effectively brought robot-assisted keyhole surgery into mainstream clinical practice. The system, originally developed for thoracic surgery, has since been employed with considerable success in areas of urology and more recently gynecology. From the surgeon's perspective, it has made certain tasks easier to perform, an example being suturing, compared to standard laparoscopic surgery. This can be attributed to the superior control architecture of the da Vinci system and the intuitive navigation of its robotic arms, which allow users to move the instrument's end effectors very naturally. This is not the case in laparoscopic surgery, where hand movements need to be reversed, in relation to end-effector movements. Employing the da Vinci system also led to a shortened learning curve for early-career surgeons, reducing the significant amount of experience-gathering time required before performing complex procedures with handheld laparoscopic instruments. Intuitive surgical's dual-console approach has also helped in this regard, enabling experienced surgeons to observe and guide novices during operations from a second console—a system not dissimilar to what is commonplace in aviation, in which a pilot or a copilot can assume control at any time.

Despite the considerable advantages of robot-assisted minimally invasive surgery (RAMIS) over laparoscopic surgery, disadvantages remain, among them the associated costs, which can be exorbitant. From a simple mechanical perspective, the da Vinci Surgical System (Intuitive Surgical Inc , Sunnyvale, CA, USA) and others such as Senhance[1] Surgical System (Asensus Surgical US, Inc.), Versius Surgical Robotic System (Cambridge Medical Robotics, Cambridge, U.K.), or the Hugo Surgical System (Medtronic, Minneapolis, MN, USA) rely heavily on structures made from long, slender, and rigid parts to achieve high performance. This severely limits dexterity, which, while not an enormous issue in procedures where the target is small, localized, and easily accessible (such as in prostatectomy), presents a significant stumbling block in more complex operations with multiple target points spread over a wide region inside a patient's abdominal cavity. In these situations, our operating tools need to move around "obstacles" (healthy organs and skeletal structures) to find pivot points from which to be able to work on their targets. This is difficult to achieve with a rigid component device without risking collateral damage to tissue.

Soft robotics technologies show a lot of promise in this context. Most importantly, by virtue of their soft nature, they are considered inherently safe for use in minimally invasive surgery (MIS). In contrast, surgical robots that are manufactured from rigid components require complex control mechanisms to ensure that the forces applied to soft tissue are kept low and, thus, to mitigate the risk of injury to the patient. Although a rare occurrence, computer failures can lead to uncontrollable robot arm movements with potentially disastrous consequences for the patient when using the traditional rigid-component robots. Soft robots also show potential in relation to new or extended surgical procedures, due to their ability to advance in a tentacle-like fashion, through narrow openings and along tortuous paths toward remote operating sites. This article provides a thorough overview of the requirements for soft robots for a range of minimally invasive procedures and highlights the challenges that will need to be addressed from a clinician's point of view.

Over the last 20 years or so, interest in a novel type of robot, the soft material robot, has surged. Fuelled by a need for devices that can operate in unstructured and dynamic environments, as well as by new developments in relation to potential materials, these novel robotic structures have been emerging from robotics laboratories around the world. An approach that has widely established itself is one based on structures made from soft materials, such as elastomers. A range of mechanisms to actuate these structures has been proposed, including fluidics, dielectrics, shape memory alloys (SMAs), and tendons. The fluidics approach, in which chambers integrated within the soft structure are pressurized to achieve articulation, is arguably the most frequently employed actuation mechanism for soft material robots [1] and, in relation to this article, takes center stage. This approach shows the most promise because actuation can be achieved locally and is fast in comparison to other actuation methods. Structurally, soft material robots are attractive due to their high structural compliance and maneuverability. In the context of MIS, manufacturing quality, miniaturization, and the development of new actuators and functional materials are the key drivers. Interfacing soft robots with appropriate user interfaces is another challenge that needs careful consideration when creating robotic devices for MIS, as surgeons, nonetheless, need to be kept in the loop.

Despite their superior ability to compliantly adapt to their environments, their virtually infinite degrees of freedom (DoFs) allowing them to circumvent obstacles, and their ability to be used relatively safely within a patient, soft robots are notoriously difficult to model and consequently difficult to navigate in a given environment. Matters are made worse by the fact that, when contact with the environment occurs, external forces are imparted on the robot causing deformations that are difficult to estimate. Rigid-component robots, on the other hand, can be represented by simple, analytical kinematic models, and thus, moving them accurately to the desired location can be easily achieved with modern control systems—clearly, a reason for their successful introduction in the manufacturing industry and in RAMIS when used in a teleoperated setting. To overcome this challenging aspect of soft robotics, researchers create and explore novel modeling techniques that take into consideration the soft robot's constituent materials and their mechanical behavior, aiming to improve navigability and positional accuracy. This article provides an overview of a range of models used in this context, with a focus on modern approaches that are based on machine learning techniques, as well as highlighting the challenges that remain.

Robots operating in complex, unknown, and unstructured environments need to be equipped with sensors to attain an understanding of their location in, and their physical interaction with, that environment. Without adequate means of perception, the robot's navigability and positioning accuracy are greatly compromised. Most recent research focuses on developing sensor technologies that can be embedded in soft robotic structures. While a plethora of sensing systems to measure the pose (position and orientation) of a rigid-component robot arm and its interactions with its environment exists, sensors for soft robots need to be developed from scratch to overcome the main challenge, which is the sensors themselves cannot compromise the key characteristic of the robot, i.e., its softness. Soft robot sensors, therefore, also need to be soft, precluding the use of existing sensors made for rigid component robots. To enhance the estimation of pose and interaction forces, sensor signals are usually combined with advanced robot models. This article provides an overview of sensing technologies that can be considered for soft robotic devices intended for surgical use within

[1]Registered trademark.

a patient. In terms of sensing modalities, the aim is to be able to identify the robot's location in relation to the surgical site and the effects of its physical interactions with the surrounding environment.

Another disadvantage of soft robots is that they perform relatively poorly when required to apply forces onto the environment, as, for example, required in tissue retraction during a surgical procedure. The ideal robot structure would be one that could change its stiffness at will from a very soft state (useful during the approach phase) to a stiff state once the target site is reached and the application of high forces onto the environment is required. The field of soft robotics has, therefore, seen increased interest in creating articulated robots that can adapt and adjust their stiffness on a task-by-task basis. Some researchers take inspiration from biology to instill robots with stiffening capabilities—the octopus, the example, is comprised entirely of soft tissue with no skeletal structure, and yet is able, using its antagonistically organized muscles, to move between soft and rigid states. When stiff, it enables the octopus to apply considerable forces to the environment [2]. Other roboticists explore approaches that are based on the principle of structural jamming. Actively jamming structural elements or particles incorporated within a soft robotic structure or jamming layers of sheets surrounding the soft robot structure have each shown promise. Other approaches are based on alloys and functional fluids that change their stiffness depending on temperature and external magnetic fields, respectively. This article reports on the most recent advances in stiffening methods for soft robots and what challenges need to be overcome to realize surgical tools that satisfy the requirements of minimally invasive procedures. This article is organized as per the structure in Fig. 1. Surgical requirements are initially analyzed, and challenges are outlined in relation to improving diagnosis and therapy in MIS. While keeping the main focus of this article on fluidically actuated soft material robots, soft technologies are presented and discussed in terms of the various elements involved; structure and materials, control, and sensing. In the conclusions, the authors assess existing devices and their future potential.

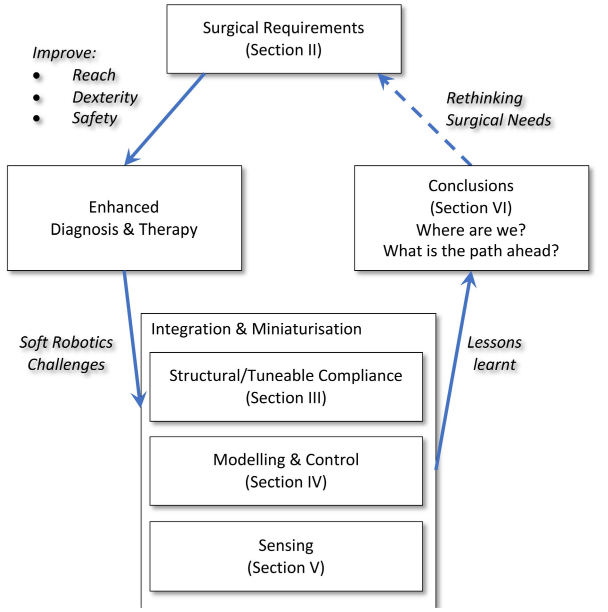

Fig. 1. *Overview of this article.*

II. SURGICAL REQUIREMENTS IN THE CONTEXT OF SOFT ROBOTICS

The overriding imperative in endoscopic diagnosis and surgical intervention is the ability to reach the target safely, efficiently, and once reached to visualize and operate on that target with a high degree of accuracy. Although we need to distinguish between diagnostic and therapeutic needs, we equally need to keep the focus on the ideal end-goal, so-called "theranostics," in which diagnosis and therapy are performed together, in a single procedure. Crucially, gastrointestinal (GI) endoscopy offers an ideal template for soft tool design, given that the GI tract is an archetypal example of soft, stretchable, adaptable, and tortuous anatomy.

A. State-of-the-Art Endoscopic Technology in Relation to Diagnosis

In terms of diagnostics, we have seen significant advances over the years with the development of radiological imaging techniques, such as computed tomography, magnetic resonance, and ultrasonography, each of which provides submillimetric precision as standard, without any transcutaneous invasion. Although these techniques are evolving in relation to the diagnosis of diseases affecting the viscera or hollow organs, they cannot supersede endoluminal imaging techniques that allow direct visualization of the epithelium lining the cavities (mucosa), histological/cytological diagnosis through tissue sampling, and operational procedures for therapeutic purposes. On the other hand, all approaches through natural orifices are difficult to perform and uncomfortable to undergo, so much so that they often require sedation or anesthesia.

Endoscopy techniques are of interest in a variety of areas, including ear, nose and throat, respiratory tract, upper GI tract (down to the duodenum), lower GI tract (small and large bowel), urology, and gynecology. The specific characteristics of the various types of natural orifices have of course influenced the development of endoscopic techniques over the years. To date, the basic endoscopic framework—used in all areas mentioned above—is based on a so-called flexible tubular instrument, albeit one that is, in truth, fairly stiff. It has an embedded vision sensor and lighting system at its tip and is articulated exclusively in the distal sector of the tube by means of a system of tie rods controlled by two wheels positioned on the handle that is operated by the surgeon. Typically, flexible endoscopes are equipped with an insufflation/irrigation system through an operating channel, which, if of adequate

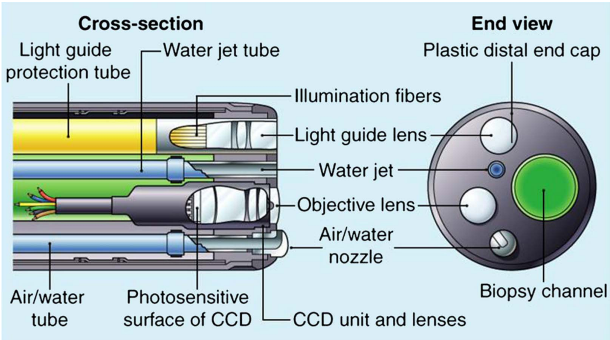

Fig. 2. ***Vision of a distal tip of a standard colonoscope including objective lens, light guide lens, illumination fibers, air/water nozzle, water jet, and biopsy channel for standard diagnosis and therapy. Figure taken from [3]. Modern colonoscopes and endoscopes outperform laparoscopic instruments by virtue of their increased flexibility. However, these are passive devices that need to be sufficiently stiff to be able to be pushed from their base into a cavity such as the colon. The applied forces can be considerable, and it is in this regard that emerging soft robotic devices, with their active actuation and high dexterity, show great promise.***

size, also allows the introduction of instruments (needles, forceps, loops, and so on) that enable it to be used for simple operative tasks (see Fig. 2). This constitutes what is referred to as a "passive" operation, in which the therapeutic actions are performed as a part of, rather than separately to, the diagnostic exploration.

From a diagnostic point of view, we have, in recent years, seen a flashback to combined "mother/baby" type endoscopic systems, i.e., endoscopes that are introduced into the operating channels of larger flexible endoscopes, to extend the dexterity of the system (see Fig. 3). These enable surgeons to access and visually explore visceral structures that would otherwise not be open to direct

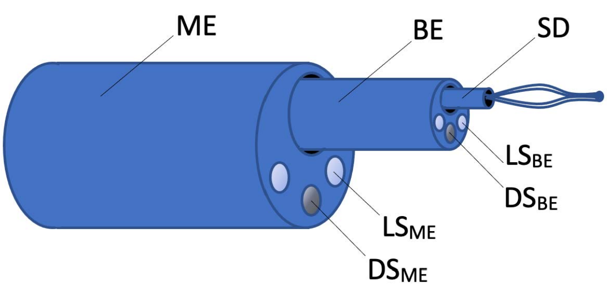

Fig. 3. ***"Mother-baby" endoscopic system for the vermiform appendix. A: mother endoscope (colonoscope/duodenoscope). B: baby endoscope. C: special device (stone retrieval basket). D: digital sensor of mother endoscope. E: light source of mother endoscope. F: digital sensor of the baby endoscope. G: light source of the baby endoscope. Figure adapted from [4]. Although somewhat flexible in nature, these highly integrated endoscopic systems need to be stiff enough to be able to be pushed into desired body cavities. As a consequence, they can cause tissue trauma and even injury when inserted.***

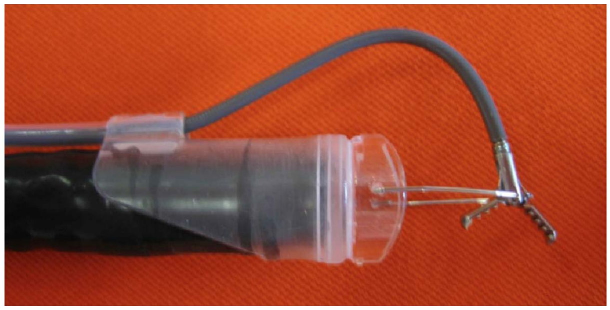

Fig. 4. ***Example of an over-the-scope accessory, external to the endoscope shaft. The EndoLifter, a single-use grasping forceps to support endoscopic submucosal dissection, a technique for local excision of digestive tract neoplasms. Image taken from [5]. Although the modular aspect of this approach shows promise, effectively expanding the capabilities of existing endoscopic devices, attaching rigid component tools can create safety issues.***

examination. These systems are currently used in biliary tract endoscopy to cannulate the choledochal and upstream hepatic ducts and in urology to visually explore ureters as far as the renal pelvis. However, they are extremely limited in functionality as their operating channels are of limited caliber, only allowing instruments of minimal dimensions to be passed through them.

B. State-of-the-Art Endoscopic Technology in Relation to Therapy

While flexible endoscopy accessories have become more sophisticated, they remain somewhat handicapped in terms of function, principally due to the size restrictions imposed by the dimensions of the operating channel. While we have seen moderate developments with the design of "over-the-scope" accessories (see Fig. 4), which can be of greater diameter, they too have their disadvantages—they need to be prepositioned and fixed to the instrument's tip at the beginning of the procedure and, because of that positioning, remain outside of the endoscopes field of view, further restricting their potential applications and increasing the risk associated with their use.

For accurate operative task completion, one must adhere to the fundamental principle of surgery, which dictates that two effectors are required to manipulate the tissue on which the task is being performed. Manipulation of tissue is the route to ensuring the precision of the operative task. An accurate dissection by surgical planes, for example, involves the separation of the layers of the bowel wall. The basic rule of any endoluminal therapy is to maintain the continuity of the bowel wall—an achievable goal on account of it having four distinct layers. The innermost, mucosa, is relatively thin and consists of monostratified or multilayered epithelium. The mucosa rests on a layer of loose connective tissue called the submucosa, which contains the vessels (both blood and lymphatic) that bring nourishment to the mucosa and drain its waste contents. External to the submucosal tunic is the muscular layer, the

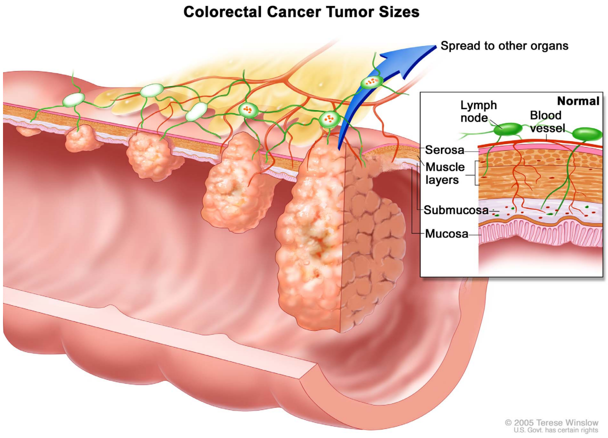

Fig. 5. ***Colorectal cancer stages and mechanism of metastatic spread through lymphatic and blood vessels. While the tumor expands into the bowel layers, the risk of lymph node and diffuse metastases increases, preventing the possibility of a curative local excision. The use of soft and compliant surgical tools becomes a necessity, as accidental disturbance of the protruding tumor needs to be avoided to minimize the risk of spreading cancer cells.***

thickest in each viscus, often itself consisting of two layers distinguished by the arrangement of the muscle fibers. Beyond that is a serous or adventitious tunic, covering and containing the bowel.

Almost all diseases of the viscera, whether infectious, inflammatory, or neoplastic, originate from the mucosa. Exploration of the inside of the bowel is, therefore, essential from a diagnostic perspective. When screening for neoplastic diseases, it is vital to diagnose neoplasms at an early stage, i.e., when they are still confined to the mucous layer from which they originate. At that stage, they can be treated locally, avoiding the need for invasive surgical dissection, as well as eliminating the need for adjuvant therapies, such as chemotherapy and radiotherapy (see Fig. 5). It is worth noting that, although the prognosis following local excision is extremely favorable, it is questionable whether, for accurate staging, it is appropriate to remove an entire piece of the bowel wall to allow the histological analysis of the depth of invasion of the neoplasm. Indeed, we already know that, once neoplasms have invaded the submucosal layer in a nonsuperficial manner, the risk that neoplastic cells have also invaded the blood and lymphatic vessels is substantial. Surgical treatment is, therefore, then required to remove the satellite lymph nodes of the affected region *en bloc,* along with the neoplasm itself. Unfortunately, it is still too often necessary to resort to radical surgery when dealing with associated loco-regional lymphadenectomy, not so much a consequence of the actual invasion of the neoplasm in the deep layers of the wall, but because of the impossibility of local excision within appropriate safety margins. Effective local treatment, alongside screening programs, would, therefore, significantly reduce the need for more invasive treatment, be that extensive surgical resection, or minimally invasive techniques, such as laparoscopy. With this goal in mind, we need to invest in research projects aimed at the miniaturization of "operating theatres" that can be transported to the desired location through natural orifices [4], [6], ideally employing soft robotic devices that move forward without applying undue pressure on the surrounding tissue.

C. Considerations in Relation to Novel Endoscopic Tools

Naturally, one must consider access options for the viscera concerned. While the oral and anal orifices are relatively compliant in relation to the GI tract, the same cannot be said for the airway and urinary tracts. Here, the gauges of the trachea/bronchi, and even more so of urethras/ureters, significantly limit the possibility of carrying simil-surgical instruments to the target area. That said, if we consider the absolute rates of neoplasms in various bodily areas, we need to place the greatest emphasis on the gastroenteric tract. While upper GI neoplasms are more frequent in Asia, in the Western world, colorectal cancers are now one of the three serial killers, having shown signs of continuous advance (at a rate of about 35%) in the last six years [7].

This justifies substantial investment both in the screening sector and endoluminal endoscopic treatments. The GI tract has been well explored in relation to its upper part (up to and including the duodenum) and its lower end (the colon or large bowel). The mid-section, the small intestine, is fortunately only rarely affected by neoplasms though it is affected by a large and worryingly increasing number of inflammatory diseases. Effective direct vision screening would facilitate safe and early diagnosis. The use of swallowable capsules that proceed passively (due to peristalsis) has proven to be a sufficiently effective nonoperative technique. The very substantial risk of causing intestinal obstruction due to the incarceration of capsules in inflammatory stenoses has been mitigated by the introduction of biodegradable "patency" capsules into clinical practice. If lodged in unrecognized stenoses of the GI tract, they dissolve within a few hours without causing major clinical problems. As an alternative, capsules could be introduced through natural orifices (mouth or anus), navigated remotely, and retrieved through the same orifice of introduction [8]–[12].

D. Requirements for Upgraded Endoscopes

Standard requirements for the improvement of endoscopes include the following.

1) Wide Spectrum and Detailed Visualization of the Interior of the Bowel, Possibly With "Image Enhancement" Techniques That Facilitate the Identification of Wall Alterations of the Bowel and Help Determine the Precise Parameters: The visual angle of the endoscope would be adapted for different applications. Currently, the standard for the upper and lower GI tracts is the use of vision sensors with a 170° range although $>140^\circ$ would be tolerable. This reduces the need for orientation of the tip of the scope while allowing the detection of a lesion across a large area. The same requirement applies to bladder inspection, which, like the stomach, is another large cavity. The study of the bronchi, urethra, ureters, and biliary tracts, on the other hand, does not require a wide-angle view. The endoscope is constricted into a narrow lumen with no possibility of moving away from the longitudinal axis. Here, cameras with a 120° viewing angle (or less) are commonly used and allow sufficient vision.

2) Tissue Manipulation by Means of Two Effectors That Are Both Controllable From the Outside That Enables Dissection by Planes Using the Correct Oncological Margins of Any Lesions Identified: The potential to miniaturize surgical-like effectors has been demonstrated in several research activities. The tradeoff lies in the ability to find the right balance between the size of the effector's arm (diameter and length), its dexterity (DoFs), and the force it can exert. These parameters also vary significantly depending on the application. In certain GI tract applications, the force (i.e., the tension) necessary to retain a stretch of visceral wall to facilitate correct surgical dissection (that respects the planes and ensures correct margins) is around 1–1.5 N [13]. If the correct tension is maintained, less force is required of the dissector tool. The type of energy that is used is also relevant. Suppose that the goal is dissection using monopolar energy—in this case, greater force is needed to ensure that the energy is applied to the smallest possible area of tissue. If, on the other hand, the intention is to use advanced dissectors (ultrasound or radio frequency), this is simply applied using the vibration of the two branches of the forceps and does not require pretensioning of the tissue to be dissected. The discussion regarding the length, and more importantly the dexterity, of the arms, is different. While it is always desirable to have as many DoFs as possible, a compromise is usually required, which addresses the need to miniaturize the toolkit. In the knowledge that current tools are "passive" and moved by their endoscopic housing, it is evident that the addition of even one single DoF would represent a step forward. Laboratory tests show that, for a surgical-like dissection of a superficial lesion, the following is sufficient: two DoFs in the manipulator's arm (i.e., bending, and longitudinal advancement) and three DoFs in the dissector arm (i.e., bending, longitudinal advancement, and rotation of the instrument tip to enable better positioning of the dissector).

3) Skilled Dissection Assisted by Monopolar, Bipolar, or Advanced Electrocoagulation Systems (Ultrasound and Radio Frequency): The ideal method for accurate dissection by planes is monopolar electrocautery, possibly with a spatula-shaped dissector. This allows both blunt dissections without energy, and sectioning of fibrous shoots whenever blunt dissection is not an option or a layer of the wall at the appropriate distance from the target lesion needs to be interrupted. This kind of dissection inevitably leads to bleeding from blood vessels in the tissue, which is best controlled by bipolar coagulation. This, however, requires instruments with two branches that are electrically isolated—a considerable technological effort while also having to remain within the acute dimensional constraints, and understandably, the reason that its development has been severely limited. Another factor to be taken into consideration is that the need to interchange instrumentation at the tip of the endoscope would lead to further technical and technological problems. The ideal scenario would be an instrument capable of combining the two functions of dissection and coagulation. It is likely that advanced dissection tools will eventually prevail, but there are several issues to be tackled. Not only does miniaturization need considerable further technological development but also endoluminal tools also need to be able to work in a humid environment (if indeed not entirely submerged as in, for example, the bladder). Not all energies can be used in this kind of environment unless liquid agents are used for the distension of the viscera. These need to be capable of controlled dissipation of energy, making them effective but not harmful to the surrounding tissues.

4) Transport of the Entire Specimen Out of the Body for Histological Examination: Until we can demonstrate that *in situ* imaging techniques can outperform traditional histological examinations for reliability, the extraction of specimens remains a necessity. While imaging techniques can help determine the nature (benign/malignant) of superficial tissue, we are far from being able to reliably determine the extent of the infiltration into the deeper layers, i.e., the information that provides a guide to prognosis and determines what kind of treatment might be required. The need to retrieve an excised piece *en bloc* poses a significant technical problem as it would not pass through standard operating channels. Fragmenting the tissue is not a solution as it needs to be analyzed in its entirety.

5) Control of Bleeding by Applying Hemostatic Glues/Powders: During dissection, there is an ever-present risk of causing a major bleed that is difficult to control using traditional basic instruments, and alternative techniques and technologies need to be made available. From a safety perspective, it is advisable to have a dedicated operative channel that enables traditional techniques, such as hemostasis, injection, application of argon-plasma coagulation (APC), and application of clips. At the same time, we need to continue investing in new hemostatic glues and powder technologies that have shown enormous promise in recent years. Ideal agents are transparent liquids that do not obscure visualization of the operating field during application.

6) Synthesis/Suture of Any Perforations (Intentional or Not) of the Bowel Wall [14], [15]: It is questionable *a* *priori* whether the objective of local endoluminal therapies should be to retain the integrity of the wall itself by leaving the outermost layers intact, or if, in principle, a piece of the wall should be entirely removed to allow greater local "radicality." In principle, a full-thickness excision must be accompanied by a system or solution that reliably restores the wall's integrity until it is consolidated by scarring. In either case, the possibility of involuntary perforation of the wall must always be taken into consideration so that the wall's integrity is never put at risk. Clipping systems have proved effective only through over-the-scope techniques and technologies, which would not allow the procedure to continue in the event of accidental perforation. Synthesis systems for sutures have proved to be complex and cumbersome. Indeed, all the systems that have been proposed over the years have failed to offer adequate levels of reliability. Even now, the systems available are applicable as standalone systems, designed for synthesis without dissection. Investment needs to focus on how to produce reliable suturing or stapling systems that make it possible to synthesize any breaches via the intraluminal route. Stapling techniques seem more easily applicable, perhaps in combination with sutures, to ensure the hermetic synthesis of the breach. The use of real suture needles is undoubtedly more complex. A good compromise is represented by shuttle-needle systems that are used as gripping pliers and which, when suitably miniaturized, could offer a solution to the problem.

E. Advantages of Soft Robot Technology

It would be advisable to direct every research effort toward the design and development of miniaturized systems that can be passed, painlessly and with minimal discomfort, into the patient's abdominal cavity via a trocar port or through natural orifices. In this context, soft robot technology offers great promise, given that several of its characteristics lend themselves to applications in the surgical field. This becomes apparent when considering the key **requirements** that would include the following.

1) Squeezability: The digestive tract is often affected by stenosis of the lumen, i.e., reduction in the internal caliber that impedes the advancement of a standard endoscope. The stenosis may be due to neoplastic growths or inflammatory bowel diseases, which would require different therapeutic strategies. The impossibility of inspection of the lumen beyond the stenosis forces us to adopt other imaging strategies, such as virtual CT colonoscopy, although this does not provide any direct vision of the GI wall. Therefore, the possibility of reducing the endoscope's diameter down to 5 mm or even less would be highly desirable. Such an advancement would be also desirable for operations in the abdominal cavity. If the soft instruments used here could squeeze through very narrow trocar ports, it would lead to considerably less trauma at the incision point for the patient.

2) Compliance: While the advancement of a standard endoscope relies on the pressure exerted on the GI wall causing passive bending of the tip, a compliant structure made of soft material would dramatically reduce the discomfort of the procedure. When the outermost layer of the endoscope made of soft materials complies with its surrounding environment, the risk of damaging tissue or organs is reduced. Compliance would result in a device that gently adhered to the GI tract lumen rather than one that exerts pressure on the bowel wall. Similarly, replacing rigid laparoscopic tools with soft ones would reduce undesired forces on soft tissue.

3) Maneuverability: Unlike rigid scopes, which are directed in one direction, by pushing from behind—and rely on the natural deformability of the bowel—the use of soft robotic technology may increase our ability to model the bowel wall and soft organ "obstacles." To do this, soft endoscopes would need to have bendable characteristics typical of soft robots, being able to follow tortuous paths with no need or at least limited use of tendons, relying principally on the pressurization of soft chambers. At the same time, they would need to be able to achieve the same level of precision as standard rigid endoscopes. In contrast with rigid robots whose movement can be described with six DoFs, movement in soft robots displays a drastic increase in the number of DoFs. That said, most soft materials have viscoelastic properties, which can lead to hysteresis, and, in turn, significant inaccuracies in open-loop control. Dynamics are further complicated by the relatively slow response of fluidic soft actuators to pressure stimuli—a consequence of the time taken for the fluid to fill the activated chamber.

4) Stiffness: From the perspective of functionality, the stiffness of soft materials needs to be adjustable. While retaining their soft properties, there are times, such as during advancement along the digestive tract or to manipulate tissue at the target site, when increased stiffness is required.

5) Sensorization: The advent of a scope that is deliberately in contact with the bowel wall or soft-tissue organs as it advances brings with it a novel concept in the field of endoluminal examination. This is the possibility of studying the bowel wall or organs in the abdomen through physical interaction. By sensorizing the outer surface of the soft robot (with pressure or force/tactile sensors, chemical sensors, or impedance sensors, for example), it would be possible to detect the presence of even small polyps or tumors and indeed also to determine the grade of inflammation of tissue, not visible via standard imaging. The types of sensors embedded into the outer surface of the soft robot depend on what we are trying to determine (polyps, tumors, inflammatory bowel diseases, and so on). Ideally, soft sensors would have minimal impact on the flexibility of the endoscope and the environment. The sensors would, therefore, also need to be compliant. They would also need to be durable enough to make this a practical option.

III. SOFT ROBOT SOLUTIONS FOR MINIMALLY INVASIVE SURGERY AND INTERVENTIONS: BALANCING COMPLIANCE AGAINST STIFFNESS

Based on the definition of *soft robots* proposed in [16], which refers to bodies that show inherent material and structural compliance, this section reviews robotic systems that are made of soft materials. As the focus will be on systems, entirely soft and hybrid robotic solutions, which consist of a combination of soft and rigid materials, are both included [17]. The fundamental compliance of soft robotic hardware, however, stems from the inherently soft materials that are used to fabricate structures, such as manipulators or sensors. These soft materials include colloids, polymers, liquids, gels, foams, fabric, granular materials, and most soft biological materials [18]. The use of these components gives soft robotic devices their key characteristics of softness, ability to bend and elongate, squeezability and flexibility, and, ideally, adjustable stiffness. These unique attributes make them ideal for a number of interventional and surgical applications, in which they can outperform their rigid counterparts in terms of safe interaction with surrounding soft tissue and maneuverability, as shown, for instance, in [19] and [20].

In Section III-A, we present a short introduction to soft robotic actuators, followed by a review of robotic solutions for optical examination (see Section III-B) and surgical tools (see Section III-C). In both cases, the focus is on endoscopy/laparoscopy, the area that is most likely to benefit from soft technologies. Systems that we have considered have all been evaluated in *ex vivo* phantom or cadaver settings. In Section III-D, we describe approaches used to control the stiffness of soft robotic devices. Section III-E outlines some of the remaining challenges and reflects on future research.

A. Overview of Soft Material Actuation Systems

Robotic movement in soft manipulators is achieved via pressurized fluids [21]–[23], tendon displacement [24], or the activation of smart materials [25], [26]. Liquid and gas fluids are used to inflate [20], [23], [27] or deflate [28] hollow chambers within soft material structures, resulting in deformations of the material. These deformations translate into bending or elongation behavior [29]. Pressurization is initiated through pipes attached to externally located devices, such as pressure regulators or compressors. A key advantage to this is that the robotic systems themselves can be miniaturized and kept to a relatively minimal weight, with the result that bending, and elongation behaviors are facilitated. Electromagnetic actuators of tendon-driven systems are also placed externally, and by pulling cables that are guided within channels along with the manipulators and fixed at their tip, bending can be achieved [30]. When deploying smart materials, such as SMAs, these metal composites have the capability to return to their initial shape after having been subjected to temperature change-induced deformation. It is this deformation that can generate driving forces that enable the actuation of soft robotic manipulators [31]. Temperature increase can be generated by running a current through the resistive SMA, in turn, causing an increase in thermal heat.

In Sections III-B and III-C, we examine soft robotic hardware systems that potentially allow for the integration of actuators and sensors for minimally invasive interventions and surgery.

B. Soft Robotic, Endoscopic Instruments for Visual Examination

The least invasive endoscopic examination involves the ingestion of capsules by the patient. Small cameras embedded within the capsule capture a large number of images when moving freely and untethered through the patient's digestive tract [32], [33]. The images are then analyzed by a clinician able to identify abnormalities that might require treatment. To overcome limitations in passive capsule endoscopy (such as lack of navigational control and inability to take a biopsy [32], [33]), a soft capsule has been proposed that can be magnetically controlled [34]. Inside the body of the capsule, a hollow needle can be guided to obtain biopsies through a soft elastomer mechanism. A permanent magnet is integrated thereby allowing actuation and tracking by moving an external electromagnet. The soft robotic capsule can, therefore, be accurately steered to the area of interest, the needle mechanism triggered, and a sample of soft tissue taken. Visual feedback is continuously obtained through an internal camera and delivered, via an interface, to the clinician. After the procedure, the device can be retrieved via the same tethered connection that supplies power and enables data transmission.

In relation to colonoscopy, inspiration has been drawn from inchworms in the creation of soft robotic manipulators [19], [20], [35], [36]. These medical devices move forward using the same peristaltic motion as their biological counterparts. One such example is the Soft Pneumatic Inchworm Double (SPID) balloon minirobot, which measures 18 mm in diameter and 60 mm in length [35]. Three hollow chambers are embedded within a structure made of soft materials, such as Vero-Clear (a transparent photopolymer) and Ecoflex 00-30 (a soft, stretchable silicone material). By fluidically pressurizing one or two chambers, bending of up to 100° can be achieved, while simultaneous pressurization of all three chambers results in elongation of the inchworm-inspired manipulator. Two inflatable balloons at the base and tip provide the requisite stability during a visual examination. A three-segment worm-inspired robotic endoscope has been designed, fabricated, and evaluated by Bernth *et al.* [20] and Alcaide *et al.* [36]. Its locomotion is fundamentally different from the fluidic-driven manipulator mentioned earlier and relies on antagonistic behavior between the outer skin of the manipulator and active actuators, such as SMAs and servomotors pulling tendons. The manipulator in [20], for example, has a 26 mm diameter with each segment about 80 mm in length. Here, an elastic crimped, cylindrical mesh creates the main body of each segment. Through tendon-driven actuation, the mesh is compressed along the manipulator's axis. Releasing the tension allows the mesh to passively achieve its default length again. Using this antagonistic actuation principle allows the robotic manipulator to move in two directions—backward and forward—as well as anchoring a segment by increasing friction between the mesh and the colon wall. An endoscopic camera is mounted at the tip providing real-time visual feedback of the soft tissue under examination.

C. Soft Robotic Systems Delivering Endoscopic Therapy

Delivering therapeutic treatment involving soft tissue manipulation with a soft robotic manipulator can only be done if it has an empty working channel. In the EU-funded STIFF-FLOP project, inspiration was drawn from the octopus arm in the creation of medical devices that could squeeze through narrow openings, bend around obstacles, elongate on demand, and allow for safe interaction between the manipulator and its surrounding environment [37]. These abilities have been proven to be advantageous in surgical interventions, such as colorectal surgery [38]. As part of the EU project STIFF-FLOP, a multisegment soft manipulator was created using Ecoflex silicone and Dragon Skin rubber materials. Each cylindrical-shaped segment of less than 15 mm in diameter and 50 mm in length consists of three fiber-reinforced chamber pairs that can be pneumatically actuated. Actuating one- or two-chamber pairs results in bending movements, whereas elongation can be achieved by actuating all chambers simultaneously. A 4.5-mm empty inner chamber allows the clinician to pass through surgical instruments or endoscopic cameras [37]. In Section VI, we examine a number of stiffening mechanisms that have been integrated into this type of soft robotic manipulator; among them granular jamming [39], the application of an antagonistic actuation principle [24], and using low melting point alloys [26], [40]. Solid-to-liquid conversion of metal composites has also been utilized in relation to single port surgery [41].

In a bid to mitigate the risk of tissue injury in endoscopic submucosal dissection, an inflatable structure that can be wrapped around the surgical instruments of a cable-driven bimanual robotic platform has been proposed [42]. Once the surgical site is reached, the structure can be inflated, significantly increasing its diameter and creating additional space for soft tissue manipulation. Using a laser welding system, hollow hexagonal prism-shaped structures are created in multilayered thermoplastic sheets. Channels for Bowden cables have been integrated into the soft structure to transmit tendon-driven actuation to the surgical instruments/end effectors.

Inspired by the longitudinal, frictionless expansion of eversion robots [43], an expandable soft robot has been created [23] with the early detection of breast cancer in mind. The millimeter-scale steerable manipulator is made by sealing low-density polyethylene using localized heat treatment. Bending motion has been achieved with tendon-driven catheters guided through the inner lumen. This free chamber also allows the passing of instruments such as miniature endoscopes, biopsy needles, and optical probes for *in situ* histopathology.

An add-on, soft hybrid robotic device for flexible endoscopes is described in [44]. The multiarticulated arm was manufactured using multiple layers of laminated stiff-flexible, biocompatible materials. Soft fluidic microactuators result in the bending behavior of the pop-up structure. A soft suction-based end-effector allows soft tissue manipulation in the endoscopic camera view. The three-DoF add-on device was evaluated inside an *ex vivo* porcine stomach.

In [45], an MR-safe soft robotic system for MRI-guided transoral laser microsurgery has been developed. The hybrid device is made of soft and hard structures, and is 100 mm long with a 12 mm diameter. The robot's two steerable segments are driven by microvolume liquid flow (<0.004 ml). Due to its inherent compliance and five DoFs, dexterous manipulation is possible within confined oral and pharyngeal cavities.

D. Controlling the Stiffness of Soft Surgical Robot Structures

One of the main requirements of surgical intervention and endoscopic diagnosis (see Section II) is for operative tools to be able to reach their targets in a safe, efficient, and compliant way and, once there, to be able to visualize and operate with a high degree of accuracy.

For this reason, the design of interventional endoscopic and laparoscopic tools must overcome the conflicting needs of being flexible enough to safely reach their targets and stiff and stable enough to carry out the interventional activity. This problem was initially outlined by Loeve *et al.* [46] with a presentation of different solutions for flexibility and variable stiffness in endoscopy (based on colonoscopy as the main application). Subsequent to that, additional reviews have been published that reflect the continued progress in relation to more specific solutions for both endoscopy and surgery, all based on soft robots [47], [48].

The problem of merging or alternating between soft and stiff structures is, of course, relevant to many applications. Traditionally, manipulators for surgical applications have rigid links and flexible/movable hinges, whose motion can be controlled, blocked, or rendered passive under external perturbations.

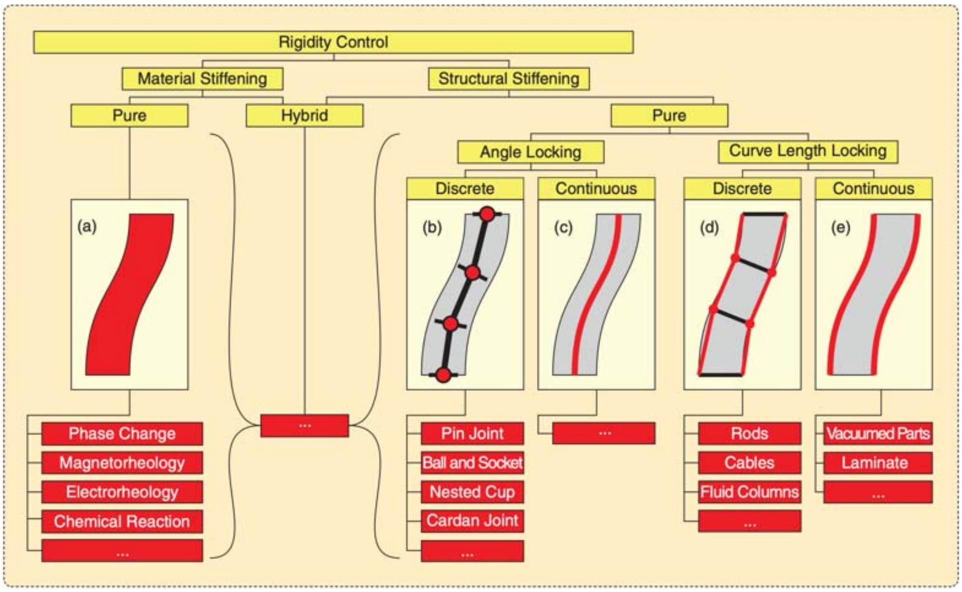

Fig. 6. ***How to control stiffness in soft robotic manipulators. These alternatives are not exhaustive, and hybrid approaches can yield further options. Again, the focus is on endoscopes rather than general surgical robots, but these methods extend to most soft manipulators. Image taken from [46].***

Free and uncontrolled motion is generally considered problematic, given the potential safety issue when bringing rigid materials into contact with soft or delicate tissue, and this is the principal reason that soft robots, fabricated with soft materials, have been developed during the past few years.

Variable stiffness solutions for the overall tool or at least for selected parts of the tool are, therefore, essential to produce forces and couples when and where necessary. As mentioned in [46], stiffness control can be achieved by material stiffening or structural stiffening (see Fig. 6). Some hybrid solutions are also possible, but, for the sake of clarity, we categorize the technologies in this way.

Material stiffening methods can exploit phase changes of materials, such as low melting point alloys or polymers [49]–[53] and functional fluids, such as magnetorheological and electrorheological fluids [54]–[56].

When selecting a solution for material stiffening in interventional applications, many issues must be considered. The overall integrability of the selected solution is key: if stiffness variability depends on a change of temperature, such as by the Joule effect, wiring issues can emerge, typically in relation to the problems inherent in integrating electrical wires with flexible and stretchable solutions. Even when stiffness variability is obtained by applying a magnetic field (which is wireless by definition), integrating coils or magnets that alter the viscosity of the fluid can be very complex and can require the addition of rigid components to a structure that needs to be soft. Although magnetorheological fluids offer valid solutions for braking systems and have been well-engineered, they have been shown to have more limited applicability in medical systems.

Another relevant aspect relates to the bandwidth of the phase change process. In many cases, phase transitions induced by temperature changes are slow, and the reversible cycle can take minutes to complete. This creates a major challenge in relation to controllability and begs the question, in relation to design, whether it is more efficient to use a solution that is normally stiff or normally soft. Biocompatibility is, of course, an added issue when operating within the body. It is mandatory to use biocompatible materials when in contact with tissues, while for materials not in contact with tissues biocompatibility can be relaxed. However, all materials, both in contact or not with the tissues, must be inert in order to mitigate issues should any kind of failure bring them into direct contact with the human body.

Structural stiffening is generally achieved by blocking/unblocking, or engaging/unengaging a structure, resulting in variation in stiffness. Conceptual solutions for structural stiffening that are achieved by locking curves or locking angles can be found, neatly summarized in [46]. In many cases, the structures to be stiffened appear as a train of many modules or nested segments in which friction plays a major role in the stiffening process. This is much like a tension cable passing through a set of concentric hemispheric elements that, when pulled tight by the cable, rigidify because of the friction between the elements. In other cases, modular robots have links that can be locked or unlocked by engaging/disengaging an internal gear system. While material stiffening simply needs a trigger for phase change activation, structural stiffening can also be achieved by way of a smart, yet traditional, mechanical design. Here, the body of a robot can be frozen in a certain configuration, despite it being fabricated from rigid materials that do not allow for any shrinkage. An archetypal example of a modular endoscopic device in which stiffening could be obtained by adjusting the tension cables used for actuation was the Neoguide [57].

The "jamming" effect is a phenomenon that can enable structural stiffening even if based on a type of phase change. It consists of a flexible and soft bag filled with small particles (or thin layers or long and thin fibers). When a vacuum is applied, the internal elements collapse, and the bag becomes extremely rigid. This effect, though not easy to model, is often considered a phase transition of these internal elements from a fluid-like state to a solid-like state. Depending on the shape and function of the device to be rigidified, the jamming effect can be created by using granular particles or fibers (for elongated and general-purpose tools, such as grippers) or by layers (for variable stiffness skins or for certain wearable technologies). The jamming effect depends on the friction between the collapsing materials, and in this regard, many studies have been undertaken to identify the most promising particle/fiber/layer/external bag combination, which maximizes friction, while minimizing weight and mitigating the risk of bag perforation during vacuum production and element collapse.

Pneumatic actuation is very commonly used as a stiffening method, either through negative pressure/vacuum as in a jamming effect or positive pressure. The success of pneumatic methods is that they can be used not purely for stiffening but also to drive locomotion, bending and elongation in soft robots.

When establishing whether to use positive or negative pressurization, it should be noted that positive pressures can be more manageable in terms of control and are, therefore, generally preferred to negative pressures, which can rarely be taken lower than 0.1 MPa, thus limiting their stiffening ability. There are some examples of positive pressurization for tunable stiffness [58] where links are pressurized in order to increase friction between components that then lock together. Recently, the authors have presented joints in which silicone rubber cylinders are embedded into rigid links, so as to achieve variable stiffness in a soft-rigid hybrid design [59], [60].

E. Discussion on Current Challenges in the Development of Soft Robotic Solutions

As soft robotic systems offer promising advantages over traditional rigid (flexible) endoscopic systems, their development has often been motivated by medical applications. However, only a small number of soft robotic medical devices have demonstrated their capabilities in anatomical phantom or cadaver environments. In general, the technical requirements of these systems are set by specific endoscopic procedures. As a typical example, MR compatibility of medical devices is usually necessary for endoscopic retrograde cholangiography. In this section, however, we will focus on the overarching challenges that exist when adopting soft robotic systems into the realm of endoscopic procedures. Fundamental challenges do remain, and their solutions will require multidisciplinary and interdisciplinary approaches, as outlined in the following.

1) Maintaining Consistent Quality in Fabrication and Manufacturing: Soft robotic systems have been created using both casting and 3-D printing techniques. Each of these methods suffers from substantial limitations, such as narrow material choice, low durability, and high variation in fabrication quality. Specific weak points of soft robotic systems occur at the interface between soft and rigid components.

2) Challenges in Miniaturization: Any medical device for endoscopic interventions must meet size requirements, creating issues in miniaturization when embedding sensing, actuation, and variable stiffness mechanisms into a soft robotic system. This is evidenced by the limited variety of miniaturized, commercially available components, such as micropumps.

3) Need for Next Generation of Actuators: Many soft robots are fluidically actuated, although pressurized fluid and proportional valves are commonly located externally due to size requirements. In cable-driven soft actuators, nonlinear friction can occur, presenting challenges in the development of mathematical models, and the transmission of forces via tendons to the distal end of a soft manipulator can affect the configuration of the soft body through which the tendons are guided. In relation to smart materials, many do require high electric currents, resulting in low actuation speed (compared to other fluidic actuation approaches) and complex control methods due to thermomechanical behavior.

4) Intuitive Interfaces for Multi-Degree-of-Freedom Soft Flexible Robotic Systems: Soft robots' continuous and elastic bodies provide, in theory, infinite DoFs. They can bend, elongate, and squeeze through narrow openings. A new generation of interfaces should enable clinicians to focus solely on the intuitive navigation of the tip of these high-DoF robotic manipulators, without having to consider the position of the body and tail, adding unwanted cognitive load and distraction.

5) New Functional Materials: Irrespective of the precise endoscopic application, soft robotic systems need to be sterile and need to be immune to fatigue of any of their components during usage. It is known that sterilization of (multiple uses) medical devices can have a negative impact on soft materials [61]. Executing a surgical procedure and manipulating soft tissue requires a level of stability and the availability of on-demand stiffness. Therefore, there is a need for new materials that are unaffected by sterilization and can also demonstrate a high degree of variability in stiffness. Moreover, they need to be able to provide this stiffening capability even when embedded in miniaturized format soft robots. The challenge of biocompatibility also needs to be considered. Materials need to be physically and chemically inert in relation to human tissue, all the while also the single most fundamental characteristic of soft robots, i.e., being soft. Ultimately, the key advantage over rigid surgical instruments is that robots made from soft materials are considerably less likely to cause tissue damage.

6) Stiffening Control: In addition to challenges of material properties and miniaturization, the requirement of stiffening control begs further questions. The first is stiffness tunability, as often we only have ON–OFF options—fine control seemingly somewhat elusive. Similarly, modeling the phenomena involved in jamming is also complex. A further issue relates to the bandwidth of the stiffening process—in the case of thermoactive materials, the cycle between stiff and soft can be quite slow, thus limiting the range of possible applications. Finally, in the case of modular soft robots, managing the actuation for bending, elongation, and stiffening can require several wires/pipes, which could only be mitigated by using distributed control components.

IV. MODELING AND CONTROL USING MACHINE LEARNING TECHNIQUES

The success of surgical robots relies on accurate control methods in addition to robotic mechanisms. Most mechanical designs of soft robots in MIS share the same basic structure with supplementary features added as required [1], [45]. As an example, endoscopes are typically used in MIS, not just in relation to therapy but also for diagnostic purposes. Their sizes (both diameter and length) naturally vary according to the body locations in which they are being used. Similarly, there are many other diagnostic and therapeutic devices, such as flexible needles and catheters, whose designs are tweaked according to their specific use. One commonality, however, apparent in all MIS robots, is in the design of manipulators that are invariably long, thin, and flexible, with a functional part at the tip (end-effector) [62]. This is a key characteristic given the need for any manipulator to compliantly reach the target through relatively confined channels. However, the increment of operational safety imposes further challenges in relation to control due to nonlinear responses of materials, low stiffness, computational expenses of complicated modeling, and integration with specific sensing modalities. Although there are studies focusing on the design and actuation mechanism of other structures, such as serial and peristaltic manipulators [63]–[65], continuum robots hold the most promise and have been subject to a greater amount of research. In this section, we discuss modeling and control in continuum manipulators, paying particular attention to those utilizing machine learning approaches.

A. Conventional Analytical Modeling

Continuum robots are usually conical or cylindrical in shape and driven by tendons or fluids. Their analytical modeling approaches can be categorized in terms of whether the geometrical approximation for the manipulator utilizes (piecewise) constant curvature (CC) assumptions. As the name suggests, in the (P)CC model, the bending body is regarded as an arc(s) with consistent

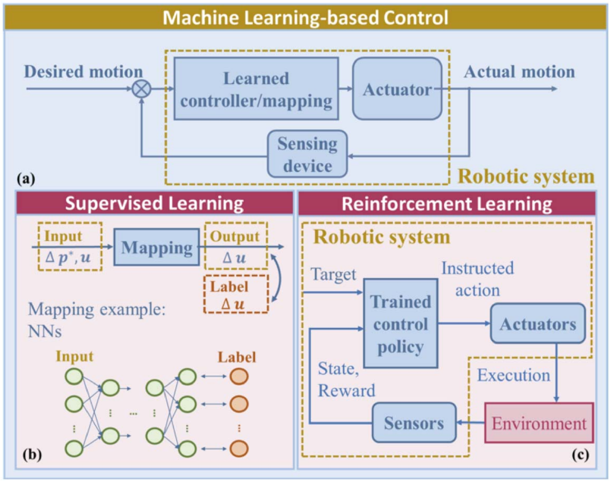

Fig. 7. ***(a) Control frameworks using machine learning approaches; applications of (b) supervised learning and (c) reinforcement learning in continuum robot control.***

curvature(s) without torsion. The corresponding kinematic models [66], finite element deformation formulation [67], static-equilibrium models (including forces) [68], or even dynamic models [69], [70] are common models that can be simply applied to soft continuum robots. However, pure (P)CC assumptions sometimes fail to reflect deformation details or resolve cases with external loadings [71]. More complex methods, such as the spring-mass model [72] and the Cosserat rod model [73], [74], have been proposed using physical mechanisms. However, as high computational efficiency and heuristic experimental calibration would be required; limited work has been validated on actual robots [75]. Another challenge comes from the demand for multiple sensing devices [76] to provide necessary configuration-related states/information for the models. Consequently, learning-based (or data-driven) approaches have attracted increasing interest in relation to the control of continuum robots, seemingly a promising substitute for conventional analytical modeling [see Fig. 7(a)].

B. Supervised Learning for Mapping Approximation

Although learning-based methods are highly dependent on sensory data, it is end-effector data that are most significant. By reducing the burden of sensing, we can circumvent the necessity of establishing configuration space, and as we know, the modeling procedure for a continuum robot's forward kinematic can be successively constructed by robot-specific mapping (from actuation space to configuration space) and robot-independent mapping (from configuration space to task space). The inverse mapping works in the opposite direction. By utilizing machine-learning techniques, the relationship between actuation space and task space can be established directly [see Fig. 7(b)], without having to consider actuation mechanisms or manipulator materials. If sample pairs of quantitative actuation commands (u) and controlled object information (end-effector pose or body shape, $\boldsymbol{p}$) can be collected, a model can be trained offline and then updated online. Forward neural networks (FNNs) are the most commonly used structures in the approximation of this type of mapping and have been successfully and widely validated on many different tendon-driven manipulators [77]: robotic tendon-driven catheters and pneumatic-driven endoscopes among them. Apart from FNN, regression algorithms, such as the Gaussian process regression (GPR) [78] or locally weighted projection regression (LWPR) [79], [80], can play the same role as supervised learning in the control loop. In accordance with the control law, inverse kinematics mapping is usually learned in absolute ($\boldsymbol{p}^* \rightarrow \boldsymbol{u}$) or relative ($(\Delta p^*, \boldsymbol{u}) \rightarrow \Delta \boldsymbol{u}$) form (where the symbol $\cdot^*$ indicates the target motion/state). In such cases, the learning-based model replaces the analytical inverse statics or Jacobian matrix. Yip and Camarillo [81] also proposed to find the optimal Jacobian matrix step by step using quadratic programming.

C. Hybrid Control Strategies

Recently, control approaches have been proposed that combine the geometrical/dynamic model with learning-based methods to accomplish specific or general control tasks. In comparison to pure learning-based methods, these approaches reduce the dependence on pure sensing data and can demonstrate good levels of performance. For example, in a study [82] on pneumatic-driven soft actuators, a dynamic control framework was designed with a feedforward component that used a neural network alongside a nonlinear feedback component. In this system, the neural network in the feedforward loop is based on augmented back propagation and solves uncertain nonlinear dynamics. Continuous tracking with no need for prior robot dynamic knowledge proved viable, demonstrating that the learning-based component can be quickly trained online by referring to the tracking error signal. In addition, an idea to superimpose a learning-based inverse equilibrium dynamics model for feedforward control was proposed, which was then integrated with a feedback controller [83]. Subudhi and Morris [84] implemented a hybrid fuzzy neural control (HFNC) scheme on a multilink flexible manipulator. Its control actions were determined by both a fuzzy controller (the primary loop) and an NN controller (the secondary loop), thus compensating for the coupling effects [84]. Tang *et al.* [85], [86] proposed a control framework combining model-free iterative learning and model predictive control for the trajectory-tracking control of a wearable soft robotic glove. The integration of the kinematic model and the machine learning trained model was also validated in a number of studies, in which the learning-based elements usually acted as an error compensator of the analytical model [87], [88]. Although not all these soft continuum robots have straightforward surgical applications, they do show great potential and could clearly be developed further.

D. Reinforcement Learning Strategies

In addition to the use of machine learning in modeling and control, another key element of deep learning—reinforcement learning—also offers promise. In this system, controllers are trained via real-time interaction with the environment, adjusting the robot's action by maximizing the reward [see Fig. 7(c)]. In an optimal control system, automatic decision-making and action generation would occur in direct response to observed state data, ultimately maximizing the accumulated reward. Locomotion [89], [90] and target tracking [91] are the principal tasks for reinforcement learning in surgical soft robotic applications. A colonoscopy application that had been trained with Q-learning and state–action–reward–state–action (SARSA) was capable of traversing the colon at variable self-adjusted velocity—an improvement on constant locomotion, particularly in tight passages [89], [90]. Policy Learning with Weighting Exploration with Returns (PoWER) was applied to refine the inverse kinematics in [92] and counter the lack of CC assumption-based modeling.

In addition to tasks such as path tracking, interventional surgical applications, such as neurosurgery and endovascular surgery, often require more rigid robotic tools, such as flexible needles and catheters. Bearing in mind the fundamental principle of not harming a patient in MIS, we need to ensure that the insertion path length is as short as possible, and anatomical obstacles are avoided. Path planning, from the insertion point to target, is, therefore, critical. Traditional path planning approaches, such as graph- and sampling-based algorithms, have limitations in terms of trajectory optimization in surgical applications [93]. As an alternative, reinforcement learning could result in the identification of optimal trajectories, while adhering to specified requirements, such as decreasing the overall path length and the possibility of contact with surrounding tissue [94]. Integration of Learning from Demonstration (LfD), Path Improvement with Path Integrals (PI^2), the deep Q-network (DQN), and universal distributional Q-learning (UDQL) have been exploited to optimize the trajectory of catheters and flexible needles with good rates of success in reaching targets and avoiding sensitive tissue [95]–[97]. Apart from the constraints of path length and avoidance, soft tissue deformation and surgical tool deflection during insertion also need to be considered. Due to the softness and elasticity of tissue, the final insertion path is prone to deviate from the planned path. Spring-mass models and finite element methods (FEMs) are usually used to estimate the biomechanical deformation of soft tissue [98], [99]. Force-deflection models [100] and experimental trials [101] could help predict needle deflection. The planning algorithm that considers these issues can refine the insertion model, resulting in better control. Indeed, a preplanned trajectory limits the motion of the surgical tool's entire body rather than purely its end-effector, thereby placing more stringent requirements on control accuracy and sensing feedback.

Other than real-time image modalities and self-contained configuration sensors [e.g., fiber Bragg gratings (FBGs)], augmented reality (AR) techniques [102] could also offer path guidance during surgery.

E. Discussion

A simulation is an important tool in robot control, generally workable in one of two ways. The conventional way is to provide a prior validation, which then acts as a virtual environment with which to test a proposed model or controller. Examples can be found in complicated geometrical or dynamic modeling approaches and task evaluation. However, the way in which we set up a soft robot simulator (especially in relation to interactions in the MIS scenario) will determine the efficacy of the simulation. The transfer of complicated parameters and the available feedback from the actual environment also need to be considered. FBG is a promising sensing device that provides strain and shape information in complicated modeling and is introduced in Section V. In the other approach, simulations not only work as a parallel testing platform but also as a necessary component in real-time control. Such simulators enable fast data collection for controller initialization or even online adaptation of the control scheme. Reinforcement learning is one of the most representative applications. There have been studies looking at da Vinci Research Kit (dVRK) compatible platforms for surgical robot learning [103]. To implement this in MIS, communication between the actuators, sensors, robot modules, and control platforms (e.g., python) will be a major difficulty. This is principally because the extraction of available real robot data and signal transmission are extremely time-consuming.

Since the striking success of (deep) reinforcement learning in AlphaGo [30], reinforcement learning has gained increasing popularity within the robotics community alongside the use of soft surgical robots in MIS. Learning-based methods circumvent the stumbling block of analytical modeling of soft robots and enable them to adapt to complex circumstances and carry out sophisticated tasks, both of which could be limited when using conventional control methods. In relation to surgical robots in MIS, it has been demonstrated that controllers/motion planners trained through learning can achieve high accuracy and satisfy specified requirements *in vivo*. However, as the quality (accuracy and distribution) of sampled sensing data is essential in regression- or iterative-based machine learning techniques, the stability of controllers could not be consistently guaranteed on each robot. In reinforcement learning, the interaction time for controller training would also be an uncontrollable factor, and this is also why more and more recent studies are aiming at transferring simulation-trained controllers to actual robots. That said, the considerable amount of precollected or online-interaction data remains the principal challenge and accounts for the fact that learning in soft robots for MIS has not yet progressed beyond research levels [104]. The strategy of shared control/autonomy has recently been attempted in soft robots, combining human involvement with machine intelligence, thereby reducing the burden on both the human operator and the automatic controller [105], [106]. For sophisticated tasks in unstructured environments, of which MIS is a prime example, shared control/autonomy could provide the basis for a novel solution.

V. SENSING FROM WITHIN: SOFT POSE AND TACTILE/FORCE SENSORS INTEGRATED IN SOFT ROBOTS

Receiving sensor signals from within the patient's abdominal cavity or from other surgical sites, such as the colon, has been recognized as an important element in RAMIS.

A. Force and Tactile Sensing in Soft Robots

Naturally, we need to receive diagnostic information from a surgical site, but, equally, it is important to be able to retrieve information about the precise location of surgical instruments and their physical interactions with their immediate environment. Tactile and force sensors integrated into surgical instrumentation can bring an important sensing modality, the provision of haptic feedback, into play. This issue became patently obvious to the surgical community as we made the gradual move from open surgery to laparoscopic surgery, effectively losing the key asset of direct haptic feedback. Indeed, it is commonly accepted that, in the past, surgeons have made very good use of their haptic capabilities, enabling them to distinguish between healthy and diseased tissue—their fingertips equipped with tens of thousands of minute tactile sensors allowing them to carry out advanced diagnostics by simply palpating the organs in question. While laparoscopy is being widely hailed as superior to open surgery because of its many advantages (among them a reduction in blood loss, trauma, scarring, and hospital inpatient duration), it comes with its own catalog of disadvantages (among them the execution of suturing, organ manipulation, and other tasks that might require coordination of two laparoscopic tools, which became considerably more complicated alongside the significant reduction in the sense of touch). The advent of RAMIS saw the latter point further heightened: the sense of touch is completely lost in current robot-assisted surgical tools, such as Intuitive Surgical's da Vinci system.

Traditionally, the vision has been accepted as a reasonable substitute for tactile and force feedback when assessing the interplay between instruments and their environment. Users of the da Vinci systems, with their superior stereo vision feedback system, claim to be able to "see" the force imparted by rigid instruments onto soft tissue by observing the deformations caused. Although there is consensus that surgeon-controlled robot-assisted surgery needs visual feedback to be successful, there is an increasing call from surgeons to augment it with haptic feedback. It is hypothesized that providing surgeons with haptic sensation would improve the quality of surgical procedures, reduce surgical margins, and reduce instances in which excessive force has caused unintended tissue injury [107]. Despite the continued reliance on visual feedback within the surgical industry, considerable progress has been made in the development of tactile and force sensors [29], [108]. More recently, technologies that enable the integration of soft sensors into soft robots have also emerged [109]–[111]. The challenge here is to take the progressive step from existing sensor technologies that are usually made from rigid components, toward new sensing options that are as compliant as the robots into which they are to be integrated.

B. Pose Sensing in Soft Robots

Aside from sensing tactile and force information, another important sensing modality is the ability to measure the position and orientation (pose) of a robot arm with respect to its environment. Acquiring the pose of a robot manipulator made from rigid links and stiff joints can be achieved easily by employing appropriate kinematic models that relate the joint positions (measured by position sensors, e.g., shaft encoders in the case of rotary joints) to the instrument's tip via the chain of rigid links that make up the overall robotic structure from the base to the tip. Using inverse kinematics, often available in analytical, closed form for rigid-component robots, the position and orientation of the instrument's tip can be computed, and by employing a suitable controller, the requisite joint motor commands can be generated to move the instrument tip to the desired location inside the patient's abdomen and then orientate the end-effector [112]. On this basis, rigid linked robot systems can easily achieve sub-1-mm accuracy levels, especially in conjunction with visual feedback in a teleoperational setup [113]. This level of accuracy is on par with what can be achieved using laparoscopic instruments. The control architecture of the da Vinci Surgical System provides a user-friendly interface that allows the surgeon to focus entirely on moving the instrument's end-effector, using the input device provided, into the desired location in a highly intuitive manner—somewhat akin to how a user moves the cursor across a computer screen using a mouse [114]. This approach greatly simplifies the execution of even the most complex procedures, such as suturing, an enormous step up from the standard laparoscopic approach in which all movements are rendered more complex by the need to allow for the fulcrum point. To reliably execute a minimally invasive procedure using laparoscopic tools, a surgeon might require years of training; using a robot such as the da Vinci system, even a novice can tie a knot into a suture after a 5-min practice session.

Although intuitive navigation of surgical instruments using a rigid-component structure is achievable in modern RAMIS systems, maneuvering a soft robot inside an abdominal cavity is not without its challenges. Extending beyond the abdominal cavity, as is the case when considering soft endoscopic systems for applications in the colon, and with natural orifice transluminal endoscopic surgery (NOTES) in general, those challenges increase because of the need to utilize considerably longer endoscopes. Given the nonlinear mechanical characteristics of a device made of soft or highly flexible materials (silicone, rubber, or fabric being examples [115]), it is difficult to derive straightforward kinematic models. Research into creating real-time models to help control soft material robots is, however, ongoing (see Section IV). These models rely on information from sensors embedded within the soft robot to compute the robot's pose and the nature of its physical interactions with the environment. Section V-C provides an overview of pose sensors and distributed tactile/force sensors in soft robotic instruments. These sensor technologies are ideally suited for integration with soft robot arms used in abdominal surgery, and other endoluminal and transluminal surgical procedures. The importance of the incorporation of diagnostic sensors is recognized but beyond the scope of this article.

C. Soft Robot Sensing Technologies

In view of the compliant nature of soft robots, it becomes apparent that the two sensing modalities of pose and kinaesthetic information (relating to forces inflicted upon the robot by its environment) are tightly interlinked. This can be illustrated by a couple of examples: 1) an external force applied to the soft robotic structure will induce bending, i.e., a change in pose, even if no actuation signal has been given and 2) even if a certain actuation signal is given that would ordinarily lead to a correspondent bending of the structure in free space, the resulting anticipated pose might not be attained if an intervening obstacle imparted a force onto the robot. Recognizing this characteristic of soft robotic behavior, it becomes clear that we need an integrated sensor system capable of separately measuring the robot's pose and kinesthetics in a decoupled manner. It is noted that this is considerably more difficult than the corresponding sensing task in stiff-joint, rigid-component robots where these two modalities are decoupled by default—indeed, a rigid-linked robot will assume its desired pose (as specified by the user) independently of external forces; it will not bend or adapt to the environment but rather move any obstacles out of the way (within the limits of the strength of its links and its joint actuator forces). In the context of robot-assisted surgery, it is evident that a robot with rigid links has the potential to cause damage to the patient if not appropriately constrained by an intelligent control architecture.

In recent years, a number of force and pose sensors with the potential to be integrated into soft surgical robotic instruments have been developed [116]. The focus of this article is on those sensors that can be integrated into the slender shafts of soft robotic surgical/endoscopic tools. Point sensors are beyond the scope of this article. It is also worth noting that there are other approaches that make use of external sensors, such as cameras and fluoroscopy (which is of considerable interest in an MIS setting), 3-D vision sensors also called red green blue distance (RGBD) sensors, and electromagnetic sensors in obtaining information about a robot's shape/pose and/or the forces experienced [1]. A further factor that needs to be borne in mind is that, whichever route we take in creating the "perfect" sensor, we cannot compromise the overall stiffness of the robot.

There have been considerable advancements in relation to sensors that are suitable for integration with slender continuum robots, such as endoscopes and catheters to measure a structure's pose. Approaches making use of grated fiber optics, commonly known as FBG, have been devised to measure shape in flexible structures. Gratings inscribed into the fiber result in a periodic variation in the fiber's refractive index behaving like a dielectric mirror reflecting specific wavelengths. Changing the distance between the gratings by bending the fiber changes the specific wavelength leading to a change in the light pattern received by the optical interrogator. The light pattern changes can be related to the amount of bending of the structure or, in other words, the shape of the structure along with different points of the structure. FBG sensors are of small diameter and as such easily integrated into catheters and endoscopes for pose estimation. FBG-based shape sensors for 1-m-long catheters have, as an example, been shown to provide good estimates of the location of the end-effector with respect to the catheter base [117]. Although they are very accurate in measuring the shape and can counter any impact from local forces due to contact with the surroundings, they also have significant disadvantages. They utilize a hugely expensive optical interrogation system to process signals from the grated fibers, whose high price further exacerbates the cost issue. Indeed, compared to light intensity modulation systems, they are about 1000 times more expensive. They also suffer from temperature drift, which needs to be compensated using additional reference fibers. Since the FBG fibers are inextensible, their incorporation into soft, stretchable robots is problematic (they cannot stretch with the soft robot). The computation of the final shape of the bending structure requires an effective model of the bending behavior of the structure.

A low-cost approach to measuring the shape of flexible structures has been proposed by Searle *et al.* [118]. This approach makes use of standard optical fibers to transfer light to the section of the structure where the shape is to be measured. In this case, the fibers act solely as the transmitters of light. Commonly, fibers are used in pairs; a transmitting fiber relays light to a mirror which reflects the light back into a receiving fiber, which, in turn, is connected to optoelectronics turning the received light into electrical, computer-processable signals. The mirror is attached to the structure in a way that, when the structure bends, it moves with respect to the tips of the transmitting and the receiving fiber, changing the light intensity reflected [see Fig. 8(a)]. The measured light intensity can then be related to the amount of bend in the structure. This approach provides good estimates of the shape of the structure in which they are embedded but is less accurate than the FBG approach. On the positive side, this light intensity-based approach is very significantly cheaper than FBG solutions, but temperature drift can also be an issue, and in terms of miniaturization, it is inferior to FBG approaches [118].

Other approaches involving optical fibers rely on the fact that fibers lose light under certain conditions when they are bent. Abraded optical fibers (fibers whose outer sheath is removed in places) leak light because the complete internal reflection inherent to commercial optical fibers is

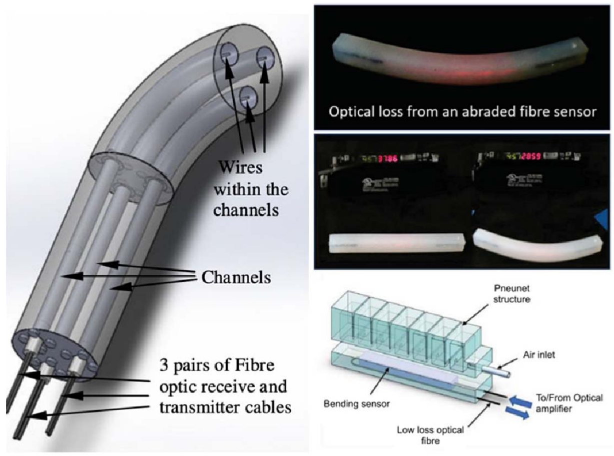

Fig. 8. ***Left: pose estimation in soft robots based on light-intensity modulation observing moving mirrors [118]. Right: soft robot pose estimation using abraded fibers [119].***

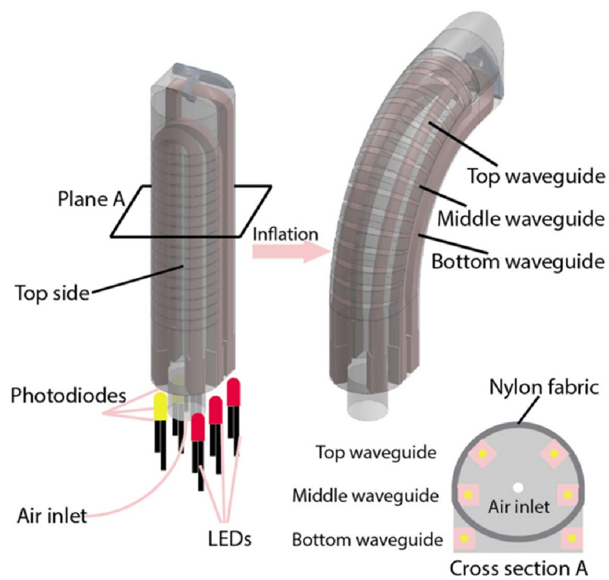

Fig. 9. ***Elastomeric, stretchable waveguide integrated with soft robot for pose and tactile measurements [121].***

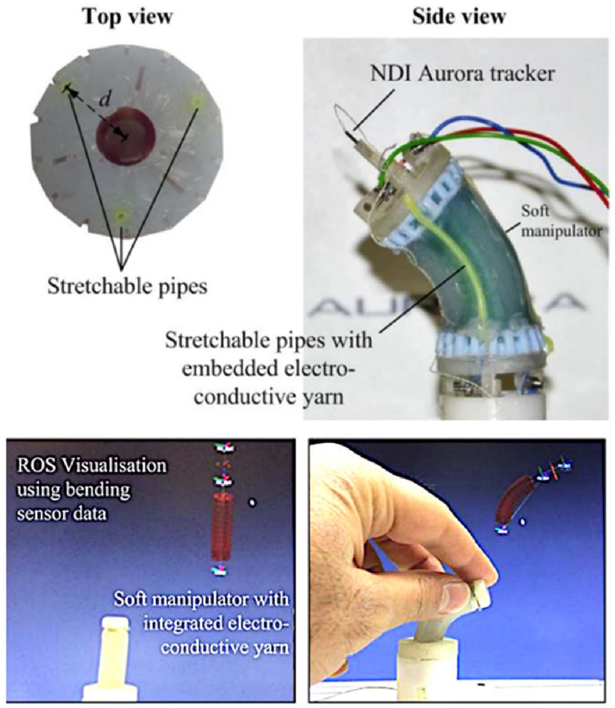

Fig. 10. ***Electroconductive yarn integrated with the soft robot to estimate pose [124].***

disturbed. The more the abraded fiber is bent, the greater is the light loss; the light intensity measured at the receiving end of this sensor can be related to the amount of bending and, in turn, to the shape of the structure [see Fig. 8(b)]. This is another low-cost approach that lends itself to the acquisition of relatively good estimates of the shape of flexible structures, but, because the optical fibers used do not stretch, incorporation of these fibers in soft, and stretchable robots is limited [119]–[121].

Extending from the idea of lossy optic fibers, researchers have created light waveguides made from transparent silicone [121]–[123]. These waveguides behave similar to abraded optical fibers—the more the silicone waveguides bend the greater the light loss—and estimates of structure shape can be gleaned in this way (see Fig. 9). Advantageously, these sensors are mechanical as soft as the material used to produce soft robots and, hence, ideally suited to integration with soft robots with no impact on the compliance and stretchability of the robot's structure. Although this approach has been applied successfully, the estimation of the structure shape is compromised by the nonlinear behavior of the material and inherent hysteresis. They are also sensitive to forces imparted on them when in physical contact with the environment. Hence, it is difficult to discern between structure shape and forces due to the interaction with the environment. These types of sensors are also bulkier than standard optical fibers, and thus, there are limits with regard to miniaturization [121]–[123].

Another interesting approach to measuring the shape of soft material structures is based on stretchable yarns that are electroresistive [124]. These yarns change their resistance when stretched, and when integrated into a soft robot, they will expand/contract in conjunction with the robot body (see Fig. 10). The approach is low cost and can easily be integrated into soft robotic devices, with little to no impact on the compliance and stretchability of the underlying structure. However, due to hysteresis and changes in resistance over time, the yarn estimates of shape are not as highly accurate as when using optical fibers.

E-gain or liquid metal has been identified as a promising sensing method for soft robotic structures. This technology can be relatively easily integrated with soft silicone robots by creating fluid-tight channels in the robot's substrate/body. The conductivity of the liquid sensing medium is altered by deformation in the e-gain-containing channels whether caused by external forces or by actuated bending in the robot [see Fig. 11(a)]. Using e-gain enables force and tactile, as well as shape sensing in soft robots [125], [126]. Although this approach produces relatively accurate measurements, the sensor signals between force and shape sensing are coupled, and additional sensing modalities and advanced modeling techniques are required to distinguish between the two. Difficulties connecting these sensors to standard electronics necessary for measurement read-out have been reported [127]. It has also

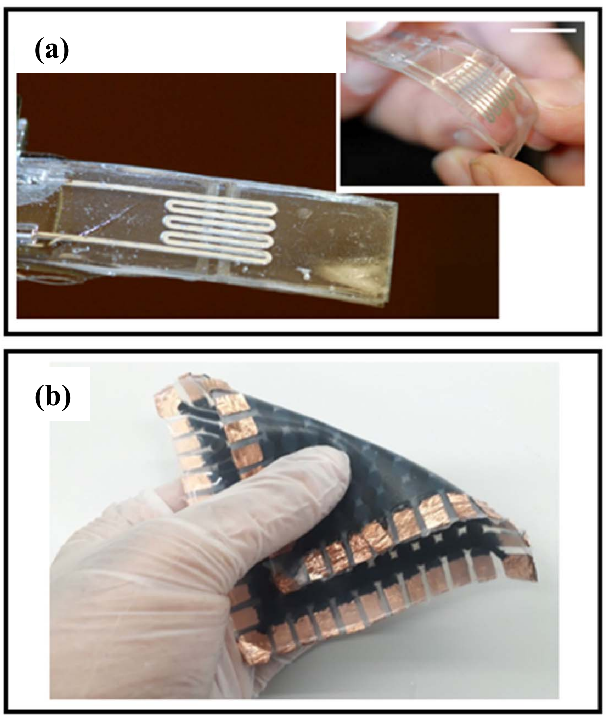

Fig. 11. ***(a) E-gain sensor integrated into the flexible substrate [125]. (b) Soft capacitive sensor integrated with the soft and stretchable elastomeric substrate [131].***

been found that the liquid, e-gain, is potentially harmful to humans, especially when in direct contact with human tissue, making it less than ideal for surgical applications [52], [53], [128]–[130].

Other researchers have focused on creating sensor skins that provide the underlying structure with tactile sensing capabilities. Those based on the principle of capacitive sensing have shown to be particularly suitable for integration into soft robotic structures [131], [132]. The e-skin developed by Dawood *et al.* [131], [132] [see also Fig. 11(b)] uses multiple elastomeric layers with carbon grease electrodes embedded between them. The carbon electrodes act as capacitor plates, while the elastomer provides the required insulation between the electrodes. The electrodes form a grid-like pattern within the sensor skin with multiple electrode strips running across the skin in parallel, at different levels separated by insulating silicone layers. As each set of electrode strips is perpendicular to its neighboring set, a matrix is achieved, which allows the collection of capacitance measurement data at high spatial resolution via terminals at the skin edges. Local deformations caused by contact with the environment lead to a change in distance between the electrodes that, in turn, lead to a change in capacitance that can be related to the applied force through a calibration process. A spatial resolution of about 8.5 mm has been achieved in sensor skins that are just a few millimeters thick. Due to their elastic nature, such skins are suitable for integration with soft robot structures for distributed tactile sensing, as they do not have any significant impact on overall stiffness. On the downside, any shape change experienced by the soft robot will also lead to changes in the measured capacitances of the skin. Current work focuses on machine learning techniques that are capable of discerning local deformation due to external forces from global bending.

In recent years, attempts have been made to estimate a soft robot's shape indirectly, for example, by way of pressure sensors (and/or airflow sensors) commonly integrated into regulators used to adjust the pressure within pneumatically actuated soft robot arms. This approach is very promising, as there is no requirement for any kind of modification to the soft robot structure—mitigating any compromise to its softness. There are, however, other significant challenges with this approach such as the requirement of a highly accurate model of the soft robot to precisely predict its mechanical behavior, despite the complexities of the nonlinear properties of the material used and the deformative effect of any physical interaction with the environment on the robot. Considerable progress has been made in the creation of control architecture that can provide a reasonably low positional error when estimating a robot's configuration (see Section III). This method can be supported by sensors introduced remotely (such as force/torque sensors integrated at the robot base to measure forces transmitted through the robot's soft body) to predict the shape of the robot.

VI. CONCLUSIONS AND OUTLOOK

This article explores the emergence of and recent developments in soft robotics, as well as the challenges that still remain in relation to the potential applications of soft material robots in MIS and endoluminal interventions.

Surgical techniques have seen tremendous progress over the last 50 years. With the arrival of laparoscopic surgery, which is performed through narrow incisions, the surgical community saw a rapid move away from traditional open surgery. It does not come as a surprise that laparoscopic surgery has established itself as the gold standard, considering its enormous advantages over earlier approaches that required large incisions and often led to high blood loss and extended hospital stays. Moving from handheld straight-line instruments to RAMIS was the next logical step allowing surgeons to carry out complex surgical procedures easily with the help of a robot and an intuitive user interface, thus partially restoring the easy-access situation of open surgery.

While today's robot-assisted MIS techniques simplify many surgical tasks, they have not been able to replace laparoscopic surgery. Given the rigidity and functional limitations of straight-line tools, and the comparative ease with which soft robots can navigate around obstacles and extend further into the abdominal cavity (alongside their inherently safe characteristics), this may seem counterintuitive. However, despite these clear advantages, there are significant challenges that need to be addressed before we can develop viable soft robotics instruments fit for MIS.

While research shows that articulated, soft material structures equipped with soft actuation mechanisms can be created to perform a range of tasks akin to what is required in the surgery, more research is needed before fit-for-purpose surgical tools are realized. Aspects such as reliable manufacturing, miniaturization, actuation, stiffness control, functional materials, and the reliable integration of soft sensors, as well as user interfaces, need to be further advanced to move soft robotics truly into the realm of medical devices.

The standard laparoscopic tool, because of its simple kinematics, can be easily integrated into a robotized system with a similarly simple kinematic structure. As recent industrial developments in the field show, teleoperation using a comfortable user interface can certainly be achieved. With soft robotics, however, the kinematics are nonlinear and highly complex. For this reason, advanced modeling techniques need to be developed to achieve surgical instruments that can be guided to a target location reliably and accurately. From analytical models to nonparametric, learned models, a range of promising approaches has been developed. More research is, however, required to ensure that teleoperation frameworks enable us to attain the same levels of navigational accuracy as is achievable with rigid-component robot systems.

Perception capability is vital for robots operating in complex, unknown, and dynamic environments. Robots need to "understand" where they are within their environment and the consequences of any physical interaction with that environment. Several researchers have created soft sensors suitable for integration into soft material robots with promising results. However, they are still not sufficiently adept in detecting whether target points have been reached within the stringent levels of accuracy required for surgical tasks. Precise measurement is difficult to achieve because soft robots commonly deform when in contact with the environment, complicating the decoupling of pose changes due to actuation from those due to external interaction forces. Advanced modeling techniques used in conjunction with embedded sensors show promise in enhancing perception accuracy.

One of the great advantages of soft robots, the ability to compliantly adapt to their environment, is, at the same time, its downfall—in certain instances, such as, when manipulating or retracting tissue in a surgical task, large forces need to be applied by the robot, and this cannot be achieved by a structure in a soft state. To overcome this challenge, more recent research explores new approaches that instill soft robots with mechanisms that allow them to alter their mechanical behavior from soft to stiff and vice versa. While considerable progress has been made in this field, stiffening approaches are still confined to research labs.

Given the above considerations, the key remaining question is whether soft robots and tools can completely substitute their rigid counterparts. The answer depends on the availability of biocompatible and reliable actuation and sensing technologies, in combination with modeling tools able to predict the behavior of the robot and in doing so help control it. What is clear is that, with soft robotics in MIS, we are heading toward a paradigm shift. Robots were originally introduced into the surgical theater to improve precision and accuracy due to accurate registration and image guidance, especially in relation to rigid organs and orthopedics surgery [133]. With the introduction of robotic tools for teleoperated abdominal surgery, such as the da Vinci system, the precision and accuracy requirements were deprioritized in comparison with the need to extend and augment the surgeon's capabilities but still within an anthropomorphic framework.

Commercial developments in RAMIS currently being pursued by several companies (among them CMR Surgical, Medtronic, Asensus Surgical, and Johnson & Johnson) are essentially variations on the da Vinci theme (introduced more than 20 years ago)—a tried and tested option that offers developers and manufacturers a potentially quick return on investment. That said, within the academic soft robotics research community, there has, since the advent of STIFF-FLOP, been a huge amount of interest and activity in developing soft robotic concepts for MIS. The fact that, despite worldwide efforts, there is little on the market, is most likely down to the stringent certification required in medical-related areas. It is likely, however, that progress will continue at a pace, and it is merely a matter of time before we see many of these concepts realized and readily available in a range of devices in clinical settings. Indeed, some application-oriented examples are increasingly close to translation—among them are a caterpillar-inspired robot for colonoscopy [134] and a miniaturized eversion robot for breast duct examination [23]. Another example can be found in the EU project STIFF-FLOP, in which it was shown that a soft robot could outperform a standard laparoscopic camera. During a human cadaver study, the soft robot used in STIFF-FLOP was able to provide the surgeon with video images of various regions within the abdominal cavity, moving around obstacles with ease and visualizing remote areas—effectively going beyond the workspace and inspectable zone of standard laparoscopes, limited, as they are, by their straight-line geometry [135].

A recent survey paper by Hawkes *et al.* [136] shows that interest in soft robotics is undiminished, indeed escalating exponentially as evident from the explosive increase in publications from ten per year at the turn of the millennium to more than 1000 per year in in the last few years. Reflecting this general surge in soft robotics, research into soft robotic surgical applications is awash with roboticists keen to capitalize on the promise that these devices offer—most obviously with respect to their capability of maneuvering through internal body cavities. This view is strongly emphasized in Dupont *et al.*'s [137] retrospective paper, declaring soft robotics as one of eight "hot topics" of the decade in medical robotics.

A great deal of soft surgical robotics research thus far has focused on creating devices that can reach inside human bodies and offer capability beyond that which is possible using standard laparoscopic instruments. The paper by Hawkes *et al.* [136] provides strong arguments as to how development in soft robotics needs to go beyond the explorative phase that we have witnessed over the past decade to establish the field as one that provides actual problem-solving tools that perform better than their rigid-component counterparts. Without this, there is a risk that the field will lose some degree of traction. The same is true for surgical robots, in which a move to Level 2 (a categorization used by Hawkes *et al.* [136] in their paper entitled "Hard questions for soft robotics" to describe the research level in which research "will not only move forward soft robotics but also advance other scientific fields and application domains more broadly") is crucial. On this basis, it is clear that there is a need to go beyond robots that move in a snake-like or tentacle-like fashion; the next generation of soft robotic solutions needs to be capable of conducting diagnostic and therapeutic procedures at the site of interest deep within the human body. Many associated challenges need to be overcome to truly usher in surgical devices based on the principles of soft robotics. Sitti [138] emphasizes this point highlighting that current "soft millirobots do not yet possess therapeutic or diagnostic medical functions." They outline the challenges (e.g., the application of high forces to carry out a biopsy) that need to be overcome in equipping miniaturized robots with medical functionality while, at the same time, recognizing the advantages this would bring.

With soft robotics, the anthropomorphic framework disappears along with concepts such as immersion—the tools no longer an extension of the surgeon's hands. What soft robotics does, however, is to highlight potential designs that are intrinsically safe and adaptable—features that relieve surgeons of the need to control all the DoFs of the soft tools. This article has demonstrated that soft body robots can potentially outperform their rigid counterparts when we need to combine multiple tasks in a single tool (e.g., retraction and tip mobility) as in single port applications or when we need to perform tasks in regions that are out of our line of sight (such as behind organs). These first credible steps are likely to pave the way for a monumental shift in the future of surgery. ■

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