Received: 17 October 2018 | Revised: 30 April 2019 | Accepted: 30 April 2019
DOI: 10.1002/rcs.2010

REVIEW ARTICLE

WILEY The International Journal of Medical Robotics and Computer Assisted Surgery

# A review on recent advances in soft surgical robots for endoscopic applications

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**Funding information**
Technical Medical (TechMed) Centre, University of Twente; Indonesian Endowment Fund for Education (LPDP)

## Abstract

**Background:** Soft materials, with their compliant properties, enable conformity and safe interaction with human body. With the advance in actuation and sensing of soft materials, new paradigm in robotics called "soft robotics" emerges. Soft robotics has become a new approach in designing medical devices such as wearable robotic gloves and exoskeleton. However, application of soft robotics in surgical instrument inside human body is still in its infancy.

**Aims:** In this paper, current application and design of soft robots specifically applied for endoscopy are reviewed.

**Materials & Methods:** Different aspects in the implementation of soft robotics in endoscope design were reviewed. The key studies about MIS and NOTES were reviewed to establish the clinical background and extract the limitations of current endoscopic device in the last decade.

**Results and discussion:** In this review study, the implementation of soft robotics concepts in endoscopic application, with highlights on different features of several soft endoscopes, were evaluated. The progress in different aspects of soft robotics endoscope, current state, and future perspectives were also discussed.

**Conclusion:** Based on the survey on the structural specification, actuation, sensing, and stiffening the future soft surgical endoscopes are recommended to fulfil the following specifications: safe especially from pressure leakage, fully biocompatible materials, MR-compatible, capable for large bending in at least two antagonistic directions, modularity, adjustable stiffness.

KEYWORDS
abdominal, digestive system, soft robotics, actuators, endoscopy, safety, sensors, endoscopy, minimal invasive surgery, natural orifice surgery

## 1 | INTRODUCTION

Minimally invasive surgery (MIS) and natural orifice transluminal endoscopic surgery (NOTES) are gradually replacing purely open surgery as less incision will reduce patient trauma and recovery duration. One of the most common form of MIS or NOTES is endoscopy. Endoscope was originally a tool only to view inside of patient's lumen, but now, it has been developed into a tool for surgical intervention, especially with the increasing trend of MIS and NOTES.

The current interventional endoscopes are either rigid or flexible. The rigid endoscopes are usually used when the target organ is near incision point. However, for distant targets, it cannot circumvent proximal healthy organs. With rigid endoscopes, the surgical operation can be performed with enough precision and force. On the other hand, flexible endoscopes are suitable for reaching distant surgical target which makes them ideal for NOTES procedure such as colonoscopy. However, flexible endoscopes lack the stability required for distant surgical intervention.[1] Therefore, there is a need to introduce modern approaches to design the surgical endoscope.

Soft robotics, inspired by nature, is an emerging field in which flexible and compliant materials are implemented in various robotic systems. This new robotics paradigm has several beneficial properties for designing new endoscopes. The materials utilized in biosoft robotics usually are biocompatible meaning that they are safe to be used inside human body (eg, silicon elastomer). Besides, the amorphous or flexible soft materials allow development of bendable endoscopes with less risk of damaging delicate soft tissues such as the wall of the colon.[2] By manipulating either intrinsic Young modulus or actuating a pair of antagonistic actuator of soft robots in different ways, stiffness of the soft robots can also be tuned.[3]

Several articles have reviewed the medical robotics for MIS applications (eg,[4-12]) most of which are outdated. Moreover, a few studies reviewed the recent developments in soft robotics actuators and sensors.[13,14] Despite all the progress in implementation of soft robotics in medical robotics application in the last decade, a review on different concepts of the designs specifically developed for endoscopic applications is missing, but can give a useful overview of the current state of the field. It can also provide an insight into the advantages and disadvantages of each mechanism for future developments.

The aim of this study was to review the previous soft actuated endoscope designs. Several related areas are highlighted. First, we present the current state and challenge of NOTES and MIS instrumentation. Subsequently, we have a brief review at how biology has inspired the development of soft robotics followed by some highlights on current soft robotics technology in actuation, sensing, and control. Several state-of-the-art conventional and soft robotics technology in surgical endoscopy are reviewed, including Invendoscopy, NeoGuide, minimally invasive neurosurgical intracranial robot (MINIR), Meshworm, and developments in the European project titled "Stiffness Controllable Flexible and Learnable Manipulator for Surgical Operation" (STIFF-FLOP).[2,15-17] New concept and design specifications for future soft endoscope are eventually discussed, based on the challenge in endoscope instruments, state-of-the-art surgical endoscope, and possibilities enabled by soft robotics technology.

## 2 | METHOD OF STUDY

The key studies about MIS and NOTES were reviewed to establish the clinical background and extract the limitations of current endoscopic device in the last decade. The key articles from soft robotics explain the knowledge of the field with specific highlight on the actuation, sensing, control, and stiffness adjustability in soft robots. A survey was performed to find the relevant articles on soft robotics endoscopes, using "*Soft Robotics for MIS and NOTES*" and "*Soft Robotics Endoscope*" as keywords. The relevant articles on soft robot design that have been preliminary tested for surgical endoscopic applications were selected. Subsequently, three most pioneering soft robot designs were reviewed as MINIR, Meshworm, and STIFF-FLOP. As comparison, conventional robotics solution for surgical endoscope, Invendoscopy and NeoGuide, were also included. Moreover, the key cited articles in the references of these studies were also investigated.

The outline of this review study is illustrated in Figure 1.

## 3 | BACKGROUND: CURRENT STATE AND CHALLENGE OF NOTES AND MIS INSTRUMENTATION

MIS has become a common paradigm of the operative medicine field during the past few decades. It requires only a few small incisions (0.5-1.5 cm) on the patient's body for surgical interventions. The potential benefits of MIS with respect to conventional open surgery are minimizing patient trauma, less blood loss, reduced risk of infection, and faster recovery. There are various applications of MIS including endoscopy, spine surgery, and percutaneous needle insertion and neurosurgery.[18]

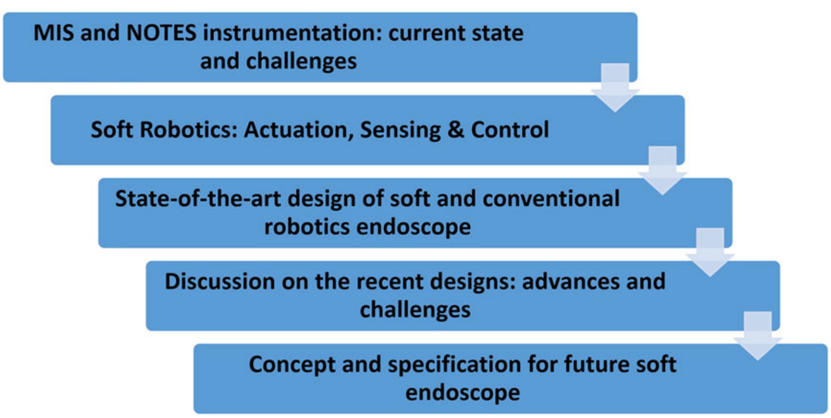


**FIGURE 1** The outline of the current review study

While MIS procedure requires incisions in the patient body, NOTES is one step further than MIS in which body natural orifice (eg, anus, vagina and mouth) is used to access the internal organ. The first reported NOTES operation applied on human was in India in 2007.[19] Despite numerous number of trials of NOTES during the past decade, until today, the adoption of such procedure remains controversial. One of the major barrier in adopting NOTES procedure is instrumentation issues.

Both MIS and NOTES use endoscope as the main surgical tools to perform surgical operation inside the patient body. Despite some promising features of the current endoscopes, they still pose several limitations for adaptation into less invasive and noninvasive surgery. As mentioned before, currently, there are two types of endoscope: rigid endoscope and flexible endoscope. Rigid endoscope, while allowing for stiff control of the endoscope, lessen the working space of the instrument as the rigid endoscope is passed through small trocar. This might pose a problem when the target organ is obscured by another organ or obstacle in front of the target organ. The rigid endoscope cannot turn around to intervene the target organ. Flexible endoscopes usually lack the stability in doing the surgical intervention, although they allow for better navigation inside the patient body.[1] To make a precise incision, the stiffness of the distal end of the endoscope needs to be adjustable.[20]

Another problem is the localization of the endoscope inside patient's body.[21] For rigid endoscope, the localization is rather straightforward as the endoscope is not inserted deeply from the incision point. However, for flexible endoscope, the view from the endoscope camera is not synchronized with the distance the endoscope has moved inside the body. There is no way up to date to verify where the endoscope is inside the body. This can cause problem when endoscope is pushed inside patient lumen. Moreover, the lack of depth perception and horizon stability make the localization of the endoscope even more challenging.

Another major limitation is the lack of maneuverability of the endoscope.[22] Rigid endoscope is clearly very limited in maneuverability. With flexible endoscope, while the distal tip can be controlled quite flexibly, the rest of endoscope tube usually cannot be controlled. To move the rest of the endoscope body, the surgeons need to push the endoscope. This method may result in the advancement of the distal tip to the wrong branch because of the lack of control and localization.

Other limitations that come from the pushing advance method of the endoscope are incomplete and painful endoscopy.[23] Incomplete endoscopy means the endoscope cannot reach the intended target. This may happen when the endoscope cannot advance in a sharp turn of the lumen. With current flexible endoscope, the lack of stiffness control might hinder the endoscope from moving forward, and it will just form a loop without being able to reach the target. On the other hand, there is a risk of damaging organ when relatively stiff endoscope is pushed forcefully through the lumen. There is a need for variable stiffness segments of endoscope that can trace various turns inside the lumen to avoid loop formation, while still enabling the flexible mode of endoscope to avoid traumatic contact inside patient's lumen.

To overcome the shortcomings in endoscopic operation, as mentioned above, several key design capabilities are required. First, for the endoscope to have flexible state and rigid state, the endoscope needs to have stiffness adjustment property. The endoscope also needs to have detectability for the surgeons to localize the robot inside patient lumen. To tackle the maneuverability problem, the endoscope needs to have bendability and controllability. While bendability means the ability of the robot to bend, the controllability means the ability of robot's segment to bend simultaneously in the predefined path calculated by a control system. Bendability and controllability, together with stiffness adjustability, are useful for preventing incomplete and painful endoscopy.

## 4 | SOFT ROBOTICS: NATURE MEETS ENGINEERING

Soft robotics, inspired by nature, is an emerging field in which flexible and compliant material is used to design and implement various robotic systems.[24] Soft robotics has several characteristics that may benefit its application in surgical robotics field. First, the robot bodies that is comprised from soft materials can comply with its surrounding environment, reducing potential of damaging tissue or organs. Second, the bendable characteristics of soft robots may provide the robotics endoscope the maneuverability to trace inside patient lumen.[25] Third, the soft materials may have the stiffness adjustable properties that enable the robotics endoscope to stiffen intended part of its body.[3] Lastly, most of the soft materials used in soft robotics can be used inside MRI bore.[26] This can introduce an MR-compatible feature for endoscopes which can solve the endoscope localization problem.

To gain insight into the soft robotics technologies, the current actuation and sensing technology used in soft robotics were reviewed. The stiffness adjustability or stiffening mechanisms of soft robots were briefly reviewed, afterwards. The challenges for the control of soft robots were also discussed in the following.

### 4.1 | Actuators

In this section, some of the most common actuators used in soft robots are briefly described. Examples of the described actuators are illustrated in Figure 2.

#### 4.1.1 | Shape memory actuators

Shape memory alloys (SMAs) and polymers (SMPs) are the materials which can deform when heated. The basic technology behind SMA is nickel titanium (NiTi) alloy wire that contracts under joule heating. Under cooling, the SMA reforms back to its initial shape.[27] The simplest type of SMP is a cross-linked glassy polymer.[14] The shape memory materials can be used as agonist actuator to generate pulling force. Moreover, their ability in recovering their original shape can be utilized to replicate complicated motions (eg,[28]).

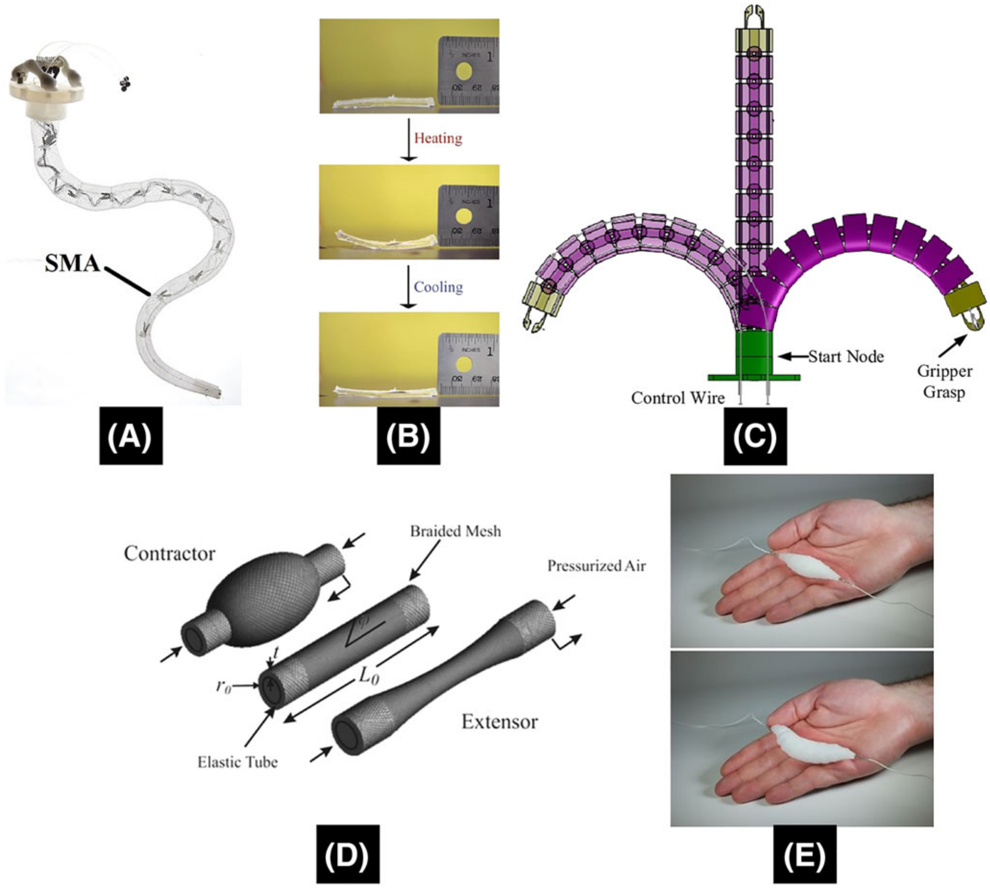


**FIGURE 2** Common actuator for soft robots: A, shape memory alloy (SMA) actuator,[55] B, shape memory polymer (SMP) actuator,[56] C, cable actuators,[57] D, McKibben actuator,[57] and E, dielectric elastomer (DE) actuator[14]

### 4.1.2 | Cable actuators

The cable actuator derives its inspiration from tendon in human body. A motor is used to generate pulling force to the cables, which in turn move or pull rigid connecting plates between body segments to apply bending. Such approach is commonly used to control continuum robots.

### 4.1.3 | Fluidic elastomer actuator

Fluidic elastomer actuator (FEA) is a type of actuator that consists of soft elastomer layers separated by a flexible, but relatively inextensible constraint. The fluid pressure needed to actuate FEA is in the range of 0.02 to 0.06 MPa. Many motion primitives are possible with FEA, including extending, contracting, twisting, and bending. There is a variation of FEA in which fibers are used to reinforce the actuator. With the tradeoff of requiring higher pressure to activate (0.17-0.24 MPa), the fiber-reinforced FEAs can exert larger force, which may be needed for several applications.[29] A common FEA actuator is *pneumatic artificial muscle (PAM)*. This type of actuator, also known as McKibben actuator, is composed of inflatable elastic tube surrounded by a braided mesh. Actuator contraction, elongation, and even stiffening can be achieved by changing the weave pattern and angle of the braided mesh. Typically, this kind of actuators works with driving pressure in the range of 0.34 to 0.68 MPa.[30]

### 4.1.4 | Dielectric elastomers

Dielectric elastomer (DE) actuators are based on the phenomenon that some materials can deform in response to electricity. These actuators were shown to be suitable choices when large strain is expected in the structure.[14,31] However, their slow response and low actuation force need to be taken into account as their drawbacks.[14]

## 4.2 | Sensors

Sensing is required for feedback control of the soft actuator behavior. Ideal soft sensors should have minimum influence on the flexibility of the endoscope. As also reviewed by Polygerinos et al, different requirements need to be considered for integration of soft sensors.[26] First, the sensor must be compliant, so it does not affect the shape or the properties of the soft robot. Second, the sensor must be durable enough to stretch for many cycles of motion. Third, the sensor should not damage soft parts of the robot. In the following, several types of soft sensing currently employed in soft robotics design are discussed.

### 4.2.1 | Resistive and capacitive stretchable sensing

The largest challenge of soft sensors is the lack of elastic material with low elastic modulus that remain conductive at high strain.[26] Alternative approaches are passive resistive and capacitive element manufactured by embedding additive resistive or capacitive element into the elastomer matrix (eg,[32-34]). However, the additive may stiffen the elastomer, so there is a tradeoff between conductivity and softness of the robot. In Figure 3, an example of this type of sensor was presented.

#### 4.2.2 | Magnetic sensing

Miniature magnet that exhibits Hall effect is embedded in robot elastomer matrix to sense the strain of the robot (eg,[36]). Noncontact nature of magnetic measurement has benefits including small dynamic artifacts, less effect on the mechanical properties of the elastomer, and small hysteresis.[37]

#### 4.2.3 | Optoelectronic sensing

Another recent solution is to fabricate and integrate waveguides into the body of the soft robots (eg,[38-40]). The power loss of the signal increases with increasing strain, because of longer pathways travelled by the light. The amount of signal loss can be used to deduce the shape of the robot.[41]

### 4.3 | Stiffening in soft robots

Currently, there are two approaches for adjusting the stiffness in soft robots: using active actuators that are arranged in antagonistic manner and using semiactive actuators that can change their elastic properties.

The antagonistic method exploits the use of active actuators that are antagonistic with each other (active-active) or are coupled with passive structure (active-passive).[3] In nature, muscle cocontraction is a good example of active-active stiffness adjustment, while muscle contraction and spring-like tendon is a good example of active-passive stiffness adjustment. In soft robotics, the active-active pairs can be achieved by pairing any of the soft actuator as explained before.

Semiactive actuators rely on the modulation of intrinsic passive mechanical properties of the material itself. Examples include stiffness controllable material such as granular jammed and layer jammed membranes whose stiffness can vary when vacuum is applied. Another example is electrorheological material (ERM) and magnetorheological material (MRM). These materials can change their stiffness when subjected to an external electric or magnetic field.

### 4.4 | Control

Accurate position and motion controls of soft robots have remained a main challenge in soft robotics. In contrast with rigid robots whose movement can be described with six degrees of freedom, soft robots can largely deform leading to a drastic increase in the number of degrees of freedom. Soft sensors and actuators usually have nonlinear dynamics, making model-based approaches difficult. Most soft materials have viscoelastic properties, which introduce hysteresis and subsequently large inaccuracies in open-loop control. Furthermore, integrated sensors are rare, complicating state estimation and feedback-control methods. Dynamics gets additionally complicated as fluidic soft actuators often exhibit slow response to pressure stimulus due to the delay caused by the time the fluid takes to fully enter the activated chamber.[26] Despite the control challenges mentioned above, for continuum robot, the kinematic model has been described.[42] As reviewed by Ros et al, the dynamic models developed for continuum robots can be expanded for some soft robots (eg,[25,43-45]).

## 5 | STATE-OF-THE-ART ROBOTICS TECHNOLOGY FOR ENDOSCOPIC APPLICATION

The integration of soft parts into small-scale system such as an endoscope poses its own challenges. First, the occupied space by actuation,

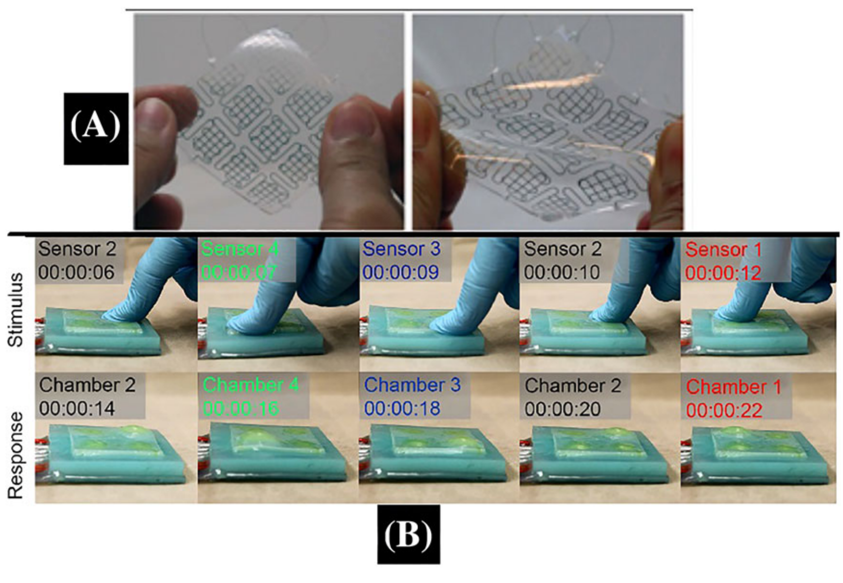


**FIGURE 3** A stretchable conductor to measure strain via measured current A,[35] and a stretchable capacitor tested to detect finger press B[14]

sensing, and stiffening components should be minimized in order to make room for free lumen inside the robot to house surgical instruments and camera. Second, in modular model, the pneumatic pipe or the cable tendon used for transmitting the power to the actuators must be routed efficiently to optimize space and avoid coupling between chambers.

After reviewing the current technology used in soft robotics sensing, actuation, stiffening, and control, the integration of these parts into a complete endoscopic system is discussed in the following. For the sake of completeness, two conventional robotic solutions were also assessed, afterwards.

## 5.1 | Minimally Invasive Neurosurgical Intracranial Robot

MINIR robot designed by Kim et al is used for endoscopy neurosurgery, especially to remove brain tumors.[15] The advantage of endoscopy in brain operation is very clear: It avoids making hole in the skull and going through sensitive area in the brain. The surgeons can insert the neuroendoscope tools through mouth or nose of the patient.

The robotic design has three segments, with 60-mm total length and a diameter of 12.6 mm. The robot has 3-mm diameter of free lumen that is used for electrocautery wires, and suction and irrigation tube. The robot has snake-like body composed of four disks interconnected by inner plastic springs. The outer part is covered by a long continuous outer spring (Figure 4). Each segment is activated by two pairs of tendons in an antagonistic manner. These two pairs of actuators enable two independent degrees of freedom motion of pitch and yaw. The tendons are actuated using SMA spring actuators, and the heat produced for actuating the SMA is cooled by cooling channels.

In the MINIR, soft plastic material called VeroWhite (Objet 350 V, Stratasys, USA) was utilized to make the body of the robot. The use of this plastic material enables the robot to be used in MR environment. The MR compatibility has been tested in gelatin slab inside MR environment, and the signal-to-noise ratio (SNR) drop is only 6.4%.[15]

Another interesting feature of this design is the use of central tendon routing mechanisms. In most of the existing robots with tendon-driven mechanism, the cable routing is done in the peripheral part of the robot (see Figure 4A, the first configuration). This makes the movement of each segment coupled, as bending the distal end will give torque along all the robot body. In MINIR design, the cable branches out from central part of the robot, toward the actuated disk (see Figure 4A, the second configuration). In this fashion, if distal tip is activated, the proximal disk will only have compression force and not torque, thus decouple the movement and control of each segment (see Figure 4B).

## 5.2 | Meshworm

The Meshworm design developed by Bernth et al was inspired by earthworm.[2] The endoscope is specifically designed for colonoscopy application. The robot is composed of three segments made of soft plastic-silicone mesh composite (Figure 5). Total length of all segments is 50 cm, and outer diameter of the mesh is 31 mm when uncompressed and 35 mm when compressed. Front and rear segments can bend about two axes, compress and elongate. Each segment is actuated by tendon wound around pulleys which are mounted on DC motors. The DC motors are small sized that they can be embedded

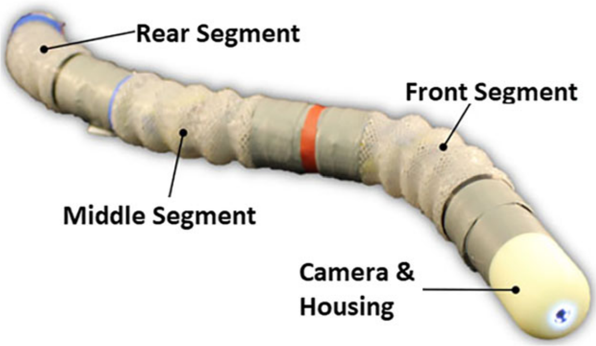


**FIGURE 5** Design of Meshworm soft robots[2]

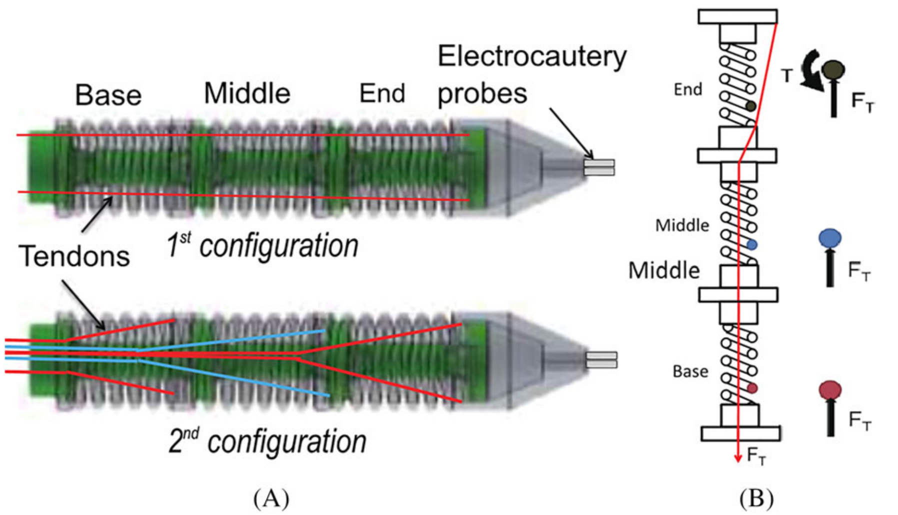


**FIGURE 4** Two configurations of tendon routing in continuum robot A, and schematic of the forces acting in base disk when distal disk is bent according to cable routing of the second configuration B[15]

inside the Meshworm. The sensing is achieved by embedding Hall effect sensor to indirectly calculate the length of each tendon. Proportional-integral-derivative (PID) controller adjusts the length of each tendon. The robot also has free lumen, and in the prototype presented, an USB camera is mounted at the end tip.

Locomotion is achieved by continuous anchoring, contracting, and unanchoring of segments. First, one end segment anchors to colon wall, increasing its friction with the wall. The middle segment of the robot then contract, pulling the other end forward. The anchoring end segment then is unanchored, followed by the anchoring of segment at opposite end. At this point, elongation of the middle segment will push the robot to the direction of first anchor point. This locomotion strategy is inspired by the earthworm.

### 5.3 | STIFF-FLOP manipulator

STIFF-FLOP is another soft robots designed for MIS application.[16] STIFF-FLOP design takes its inspiration from octopus arm. Octopus arm is highly squeezable and capable of multidirectional bending and stiffening. Those capabilities will benefit a soft surgical manipulator.

In the first design of STIFF-FLOP, pneumatic actuation is combined with granular jamming to implement the desired capabilities. Pneumatic actuator is employed for achieving multidirectional bending and elongation, while granular jamming is applied for varying the stiffness. The manipulator bodies are constructed from flexible and soft silicone elastomer, which enables the squeezing of the robot.[16] The robot consists of three fluidic chambers equally spaced in radial arrangement embedded in an elastomeric cylinder. The cylinder is then enveloped by a crimped sheath to limit the radial expansion of the chamber when inflated. Outer diameter of the overall module is 32 mm. By activating one fluidic chamber, the manipulator will bend away from the activated chamber. By activating two fluidic chambers, the manipulator will bend in direction between the two activated chambers. Activating all chambers will elongate the manipulator. The granular jamming chamber is made of latex membrane filled with coffee powder and inserted in an 8-mm channel in the center of the STIFF-FLOP module. Jamming is induced by applying vacuum to the chamber. The design pursued by STIFF-FLOP used modular approach. Each module has the same stiffening and bending capability, and the length required for specific surgical purpose determines how many modules are needed.

The first design of the STIFF-FLOP has several shortcomings which were addressed in the second design. The application of pressure into the semicylindrical chamber caused the chamber area to increase. The increase in chamber area makes the chamber more sensitive to pressure changes. The other drawback of increasing chamber area is the change in chamber cross-sectional center. The chamber cross section moves toward the center of the module, reducing the moment arm. This in turn causes less bending moment than what can be fully achieved. Another problem is that external sheath caused a friction between the sheath and the internal silicone, causing some actuation energy to be wasted in friction.[46] Fras et al suggested three improvements to STIFF-FLOP such as removing the external sheath, employing braiding on each actuation chamber, and making the chamber into cylindrical cross section (Figure 6). The braided chamber and cylindrical cross section result in more optimal elongation and limit the radial inflation.[46,47] Removal of external sheath eliminates the friction with internal silicone elastomer.

The second design is improved furthermore with the focus on size reduction by excluding the central granular jamming membrane. The removal of this membrane opens space for free lumen inside the manipulator. The lumen can be used for housing camera or other surgical tools. Other improvement is the shift from one pneumatic chamber into a pair of pneumatic chambers. A pair of pneumatic chamber will make the moment arm farther from the center of the robot, thus increasing the bending moment and stability.[48] Overall diameter of this third-generation design is 14.5 mm; this size fits into trocar for MIS operation. Moreover, the two-module design is implemented and tested in human cadaver and proved the reaching and bending ability of the manipulator.

### 5.4 | Conventional robotics solutions

The state-of-the-art conventional robotics endoscopes (FDA approved) reviewed in this paper are Invendoscopy (Invendo Medical GmbH, Germany) and NeoGuide (NeoGuide Endoscopy System Inc, Los Gatos, CA).[17]

Invendoscopy (Figure 7) consists of reusable single handheld controller, processing unit, and single use colonoscope.[49] The colonoscope

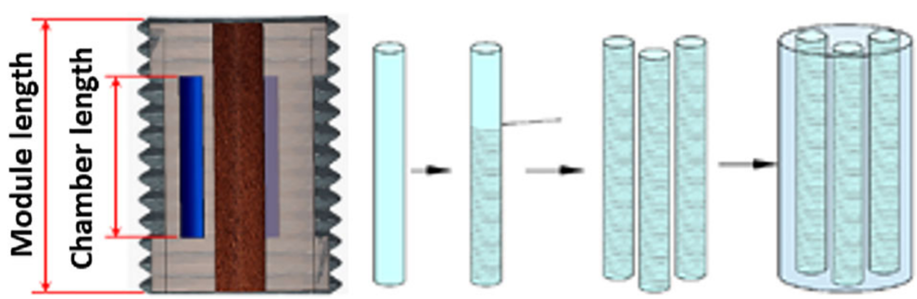


**FIGURE 6** The first design of Stiffness Controllable Flexible and Learnable Manipulator for Surgical Operation (STIFF-FLOP) manipulator, with semicylindrical pneumatic chambers and external braided sheth (left). Improvements by Fras et al by using braided cylindrical pneumatic chambers and eliminating the external sheath (right)[46]

**FIGURE 7** The tip of Invendoscoy E20 (left) and NeoGuide (right)[17]

can be inserted as deep as 170 cm. The tip is bendable up to 180° in all direction. Tip bending radius of 35 mm enables retroflection and colon visualization. This endoscope also has a 3.1-mm working channel for housing surgical instruments. However, this robotic solution still uses manual pushing insertion as its advancing method.

NeoGuide colonoscope consists of 16 equally sized electromechanically actuated modules to form a snake-like structure which can trace the lumen using computerized mapping (Figure 7).[50] The NeoGuide uses programmable overtube that prevents loop formation, thus avoids painful and incomplete endoscopy.[51] The tip of NeoGuide can be guided to all direction.[50] The localization problem is tackled by external position sensor that measures the robot depth. NeoGuide also enables two modes: passive and active modes. In the passive mode, the endoscope is relatively stiff. Multiple-level stiffness control and independent stiffness control of each segment have not been reported.

## 6 | DISCUSSION: ADVANCES AND CHALLENGES OF RECENT DESIGNS

In this section, we assess the designs described in previous section with regards to four crucial capabilities for endoscope: stiffness adjustability, detectability, bendability, and controllability. The summary of all the designs presented in previous section evaluated against the four important soft endoscope capabilities is presented in Table 1.

Environment compliant, safe interaction with organ, and ability to undergo dexterous deformation make soft robotics very promising approach for endoscope design. The benefit of these properties can be seen in the worm structure presented in Meshworm. The worm structure enables dexterous navigation inside the human lumen. Another benefit can be derived from octopus tentacle design presented in STIFF-FLOP. The octopus tentacle concept is useful for designing the tip of endoscope capable of bending, stiffening, and exerting large force. In general, the soft robotics solution performs well in terms of bendability and maneuverability.

Stiffening adjustability is beneficial in therapeutic endoscope device. Compliant soft body is convenient for navigation of the robot inside human lumen. If the robot approaches the operation site, then area around its distal part will stiffen, enabling precise control of the tip. Although the first design of STIFF-FLOP already has stiffening mechanism, it does not have internal free lumen to house surgical instruments. The lumen is then added in the third design of STIFF-FLOP; however, the granular jamming for stiffening is no more implemented.

By trying to eliminate electric or magnetic field using for instance pneumatic soft actuation, the integration of imaging modalities such as MRI will be of additional benefit. With the help of the visual feedback from MRI, the problem of endoscope localization can be tackled. This approach has been used by MINIR to localize the robot.[2] Another solution for localization can be using position sensor like in NeoGuide[17]; however, this sensor might interfere with MRI.

## 7 | CONCEPT FOR FUTURE SOFT ENDOSCOPE DESIGN

After reviewing the current designs, a new concept for endoscopic surgery which is remote endoscopic operation under MRI-based guidance seems to be promising.[15,52] An MR-compatible soft robotics endoscope enables the surgeon to perform the surgery while the patient is inside MR scanner. The real-time MR images during the endoscopic operation provide the surgeon with detailed information which can be beneficial to prevent localization problem. With a real-time tracking implementing imaging modalities (eg, MRI), the position of the endoscope and the condition of the organ can be continuously monitored, and required corrections can be made by the operator.

**TABLE 1** Design vs specification for soft and conventional robotics endoscope solution

| Design Aspect | NeoGuide | Invendoscopy | Meshworm | MINIR | STIFF-FLOP First Generation | STIFF-FLOP Third Generation |
|---|---|---|---|---|---|---|
| Stiffness adjustability | Yes | No | No | No | Yes | No |
| Bendability | Yes | Yes | Yes | Yes | Yes | Yes |
| Detectability | Yes | No | No | Yes | No | No |
| Controllability | Yes | No | Yes | Yes | Yes | Yes |

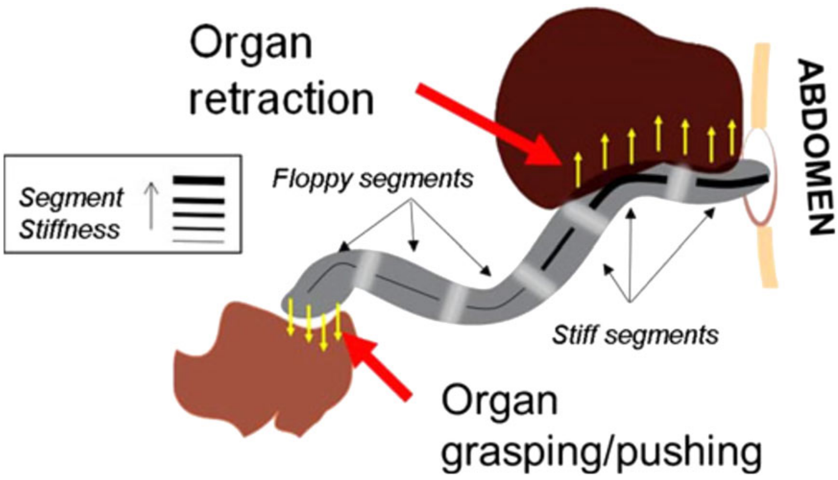


**FIGURE 8** Scenario of an endoscope that stiffen its proximal end to retract an organ and stiffen its distal end to perform surgical operation[54]

From maneuverability standpoint, bendable modular continuum robot already has both forward and inverse kinematic model.[42,53] Since most of the current sensing modalities interferes with the MR compatibility of the robot, open-loop control using kinematic model can be implemented. This method has been tested by Abidi et al to control two segments of STIFF-FLOP.[48] Instead of pushing the endoscope along patient lumen toward target organ, now it is possible to bend some segments of the robot to avoid painful endoscopy. More sophisticated control method may use path planning algorithms based on kinematics model of modular continuum robot and the intended path created from MR images. Path planning approach has been implemented in NeoGuide.[17]

Another consideration in endoscope design is the stiffness adjustability of the robot. It is preferable that the robot has several stiffness levels. This will offer the surgeon a variety of stiffness levels needed for different endoscopic operations in terms of interventional instrumentations and operation type (eg, biopsy, inspection, etc) on different organs. Besides, independent stiffening of the endoscope segments can give more freedom of control to the surgeon during the operation. One example is to stiffen some segments of the endoscope to tract proximal organ while the distal end of endoscope is also stiffened to perform biopsy (Figure 8).

The modular design in all soft surgical robots presented in this review is a promising approach in building continuum robots. The modular design facilitates the manufacturing process in blocks. Other benefit includes the flexibility to adjust the length of the robot as necessary for specific applications. From the design point of view, first one module proof-of-concept design can be realized and tested, before moving to multimodule design.

In this review study, the implementation of soft robotics concepts in endoscopic application, with highlights on different features of several soft endoscopes were evaluated. The progress in different aspects of soft robotics endoscope and current state and future perspectives were also discussed. Based on the survey on the structural specification, actuation, sensing, and stiffening the future soft surgical endoscopes are recommended to fulfil the following specifications: safe especially from pressure leakage, fully biocompatible materials, MR-compatible, capable for large bending (at least 90°) in at least two antagonistic directions, modularity, and adjustable stiffness.

## ACKNOWLEDGMENTS

The authors would like to thank Technical Medical (TechMed) Centre, University of Twente, for their financial support to the Soft Robotics project. The authors would like to also thank Indonesian Endowment Fund for Education (LPDP) for their financial support to M.W. Gifari.

## CONFLICT OF INTEREST

The authors declare no potential conflict of interest.

## ETHICAL DISCLOSURE

This review article does not contain any experimentation on any subject.

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**How to cite this article:** Gifari MW, Naghibi H, Stramigioli S, Abayazid M. A review on recent advances in soft surgical robots for endoscopic applications. *Int J Med Robotics Comput Assist Surg*. 2019;15:e2010. https://doi.org/10.1002/rcs.2010