Biomimetic Intelligence and Robotics 4 (2024) 100168

Contents lists available at ScienceDirect

Biomimetic Intelligence and Robotics

journal homepage: www.elsevier.com/locate/birob

Review

Variable stiffness methods of flexible robots for minimally invasive surgery: A review

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ARTICLE INFO

Article history:
Received 26 February 2024
Revised 30 April 2024
Accepted 21 May 2024
Available online 4 June 2024

Keywords:
Minimally invasive surgery
Continuum robot
Variable stiffness

ABSTRACT

With high flexibility and slim body, flexible robots have been widely used in minimally invasive surgery because they can safely reach the lesion deep inside the human body through small incisions or natural orifices. However, high stiffness of robot body is also required for transferring force and maintaining the motion accuracy. To meet these two contradictory requirements, various methods have been implemented to enable adjustable stiffness for flexible surgical robots. In this review, we first summarize the anatomic constraints of common natural tracts of human body to provide a guidance for the design of variable stiffness flexible robots. And then, the variable stiffness methods have been categorized based on their basic principles of varying the stiffness. In the end, two variable stiffness methods with great potential and the moving strategy of variable stiffness flexible robots are discussed.

1. Introduction

1.1. Flexible surgical robots in minimally invasive surgery

Minimally invasive surgery (MIS) includes single or multi-port surgery and natural orifice transluminal endoscopic surgery (NOTES), as shown in Fig. 1. MIS offers advantages such as decreasing the pain of the patient, reducing the recovery time, enhancing the safety of the surgery, etc. Therefore, it has become prevalent in past decades, and robot-assisted MIS has also developed rapidly [1,2].

The surgical instruments are required to have a dexterous and slender body, which allows them to access the lesion deep inside the human body and carry out surgeries during MIS. Therefore, flexible robots with small outer diameter and plenty of degrees of freedom for maneuverability are used widely in MIS [3].

However, the high dexterity of flexible robot can also be drawbacks in some situations. During the surgery, robot's body may be too flexible to withstand the external force generated by the human body, resulting in low working accuracy and stability of the robot. And low stiffness also limits the robots' performance in force transmitting and some motions that need higher force [4], like grasping, puncturing, and being tract of other surgical instruments, etc. Furthermore, robots may face many problems when advancing into human body, like forming undesired twist after contacting the organs, which prevents the robot to move forward any more.

Then two contradictory clinical demands arise: a flexible MIS robot is required to be low-stiff and dexterous in order to safely reach the lesion, but it is also required to be high-stiff when performing surgery, aiming to improve its operational stability, precision, and the capability of exerting force. Hence, variable stiffness has became a desirable ability of flexible MIS robots [5].

1.2. Variable stiffness in flexible robots

Stiffness is an important characteristic of robots, which relates to their dynamic performance and interaction with environment.

Four commonly used stiffness calculation methodologies of flexible robots have been summarized from previous studies, as shown in Fig. 2.

First, the robot's stiffness can be calculated as the proportion of the deviation of robot's end-effector from the corresponding external force [8,9]. When an external force is applied to the robot's distal end, as shown in Fig. 2(a), the stiffness K can be expressed as

$$K = \frac{d}{F} \tag{1}$$

where d and F are the magnitude of deviation and external force, respectively.

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[1] Given Shuang Song's role as Guest Editor and Jiaole Wang's role as Managing Guest Editor of this journal, Shuang Song and Jiaole Wang had no involvement in the peer-review of this article and had no access to information regarding its peer-review. The article was handled by Prof. Yangming Lee.

https://doi.org/10.1016/j.birob.2024.100168

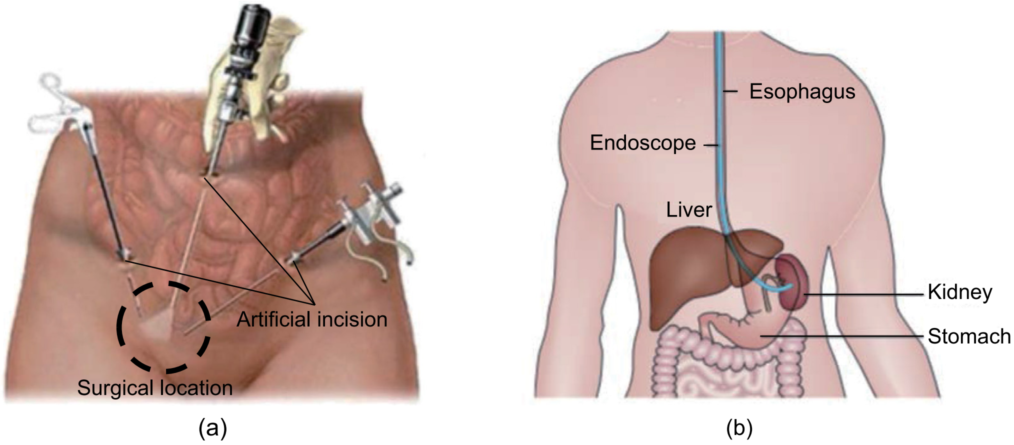


Fig. 1. Minimally invasive surgery. (a) Multi-port minimally invasive surgery [6]. (b) Natural orifice transluminal endoscopic surgery [7].

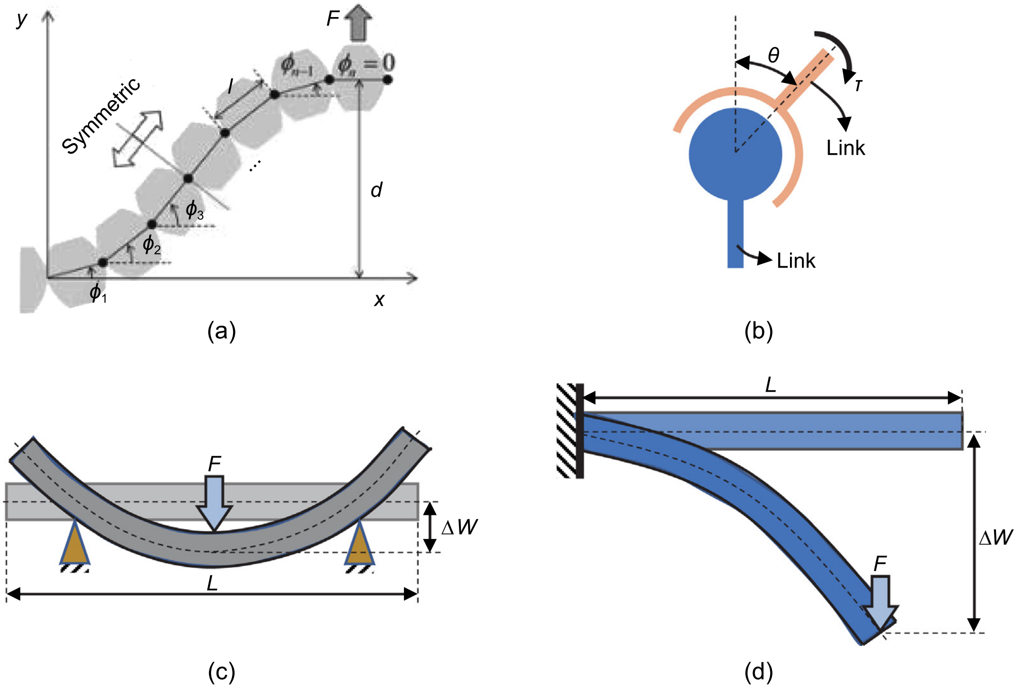


Fig. 2. Calculation methods of flexible robot's stiffness.

When an external torque is applied to the robot, as shown in Fig. 2(b), the stiffness K can be expressed as

$$K = \frac{\theta}{\tau} \tag{2}$$

where θ and τ are the magnitude of rotation angle of robot and the external torque, respectively [10].

Additionally, the stiffness of robot can also be calculated by elastic beam theory. By setting the robot as a beam with two support and applying an external force on the middle [11,12], the stiffness K can be calculated as

$$K = EI = \frac{FL^3}{48\Delta w} \tag{3}$$

where E is the flexural module, I is the moment of inertia, L is the length of robot, F is the magnitude of external force, and the Δw is the deviation of robot's middle, as shown in Fig. 2(c).

By setting the robot as a cantilever beam and applying an external force on the distal end [13,14], the stiffness K of robot can be calculated as

$$K = EI = \frac{FL^3}{3\Delta w} \tag{4}$$

where E is the flexural module, I is the moment of inertia, L is the length of robot, F is the magnitude of external force, and the Δw is the deviation of robot's end, as shown in Fig. 2(d).

Since there are multiple stiffness calculation methods, readers should be aware that stiffness values in different works may have different dimensions. Additionally, we have introduced the concept of stiffness adjusting ratio to intuitively show the stiffness improvement that each variable stiffness method can achieve. The stiffness adjusting ratio is calculated as the proportion of maximum to minimum stiffness of the variable stiffness flexible robot [15,16], which is a dimensionless parameter.

By adjusting the stiffness, robots can enable many valuable functions like safe human–robot interaction, force sensing, efficient energy harvesting, programmable force output, etc [17,18].

Table 1
Classification of common variable stiffness methods.

Classification		Description	Reference
Antagonism of internal force		Adjusting the antagonism between internal forces to vary the robot's stiffness.	[9,23–37]
Constraint of relative motion	Friction-based constraint	Adjusting the friction between the movable structures, the motion of which is coupled with the robot's deformation, to vary the robot's stiffness.	[8,38–54]
	Mechanical engagement (Locking)	Using engageable structures on the movable mechanisms, motion of which is coupled with the robot bending, to lock the robot's shape.	[30,55–59]
Use of variable stiffness material	Phase transition material	Using materials that can change their stiffness with different energy input to vary the stiffness of robot.	[11,12,14,60–75]
	Rheological fluid	Using rheological fluid, whose viscosity is changeable, to vary the robot's stiffness.	[76–80]

Many variable stiffness mechanisms have been applied on large-scale robots to change performance. For example, prostheses enhance their adaptability in different working scenarios by equipping with spring-based variable stiffness mechanisms [19], robot maintains precise force sensing ability by real-time controlling the joint motor [20], continuum robot output programmable force by using pneumatic based variable stiffness outer sheath [21], etc.

However, since flexible robots are constructed with consecutive joints or continuum elastomers, which featuring slim bodies and small cross sections, common variable stiffness mechanisms with large scales cannot be applied to the robot. Therefore, novel variable stiffness methods for flexible robots have been proposed [22], including implanting low-melting-point material (LMPM) or shape-memory material (SMM), using jamming or lockable mechanisms, etc. In the following sections, these commonly used variable stiffness methods for flexible robots have been categorized and elaborately introduced, along with interesting applications.

1.3. Scope of article

In this paper, we focus on development, challenges, and future of the variable stiffness methods for flexible MIS robots. Common variable stiffness methods are categorized based on their fundamental principle of altering robot's stiffness, and the characteristics of each method are elucidated, which can help readers understand how to select the suitable methods. After summarizing the challenges and requirements of current variable stiffness methods, we introduced two potential methods with great properties, which may aid users in exploring the ideal method.

Furthermore, we have discussed the ability of avoiding obstacles and following predetermined path for variable stiffness flexible robot, with the intention of uncovering their potential applications in other domains, such as manufacturing, rescuing, aerospace operating, etc.

2. Variable stiffness method

Common methods of varying flexible robots' stiffness can be categorized into three types, by using antagonism of internal force, constraint of relative motion, and variable stiffness materials, respectively.

More detailed classification and examples of applications are shown in Table 1 and Fig. 3. A collection of variable stiffness flexible robots are shown in Table 3, including the each robot's variable stiffness principles, outer diameter, stiffness adjusting ratio, response time, and brief description.

2.1. Antagonism of internal force

Changing antagonism of the actuators is the most common way to change stiffness of the structure in nature. For example, human muscles on the both sides control the joint to rotate oppositely. When the two groups of muscles contract at the same time, the overall external stiffness of the joint will increase significantly. With the same principle, to adjust the flexible robot's stiffness, researchers can enhance the internal force, like increasing the actuation forces simultaneously, to mitigate the influence caused by external disturbance forces, as shown in Fig. 3(a).

Many proposed flexible surgical robots have used this principle to vary stiffness. Falco et al. [23] designed a variable stiffness percutaneous needle for minimally invasive surgery, as shown in Fig. 4(a). The variation of tendons tension can adjust the stiffness of robot, which is suitable for puncturing different tissue. Kim et al. [9] designed a hyper-redundant tubular manipulator composed of special shape links, which can achieve variable neutral-line during moving, as shown in Fig. 4(b). With these links, the robot can achieve continuously changed stiffness by varying the tension of tendons even during moving. Wakimoto et al. [29] designed an intestine endoscope like continuum robot with fiber-reinforced rubber tubes inside, as shown in Fig. 4(d). As air is pumped in, the pressure of the tube increases to resist bending, and the robot's body is stiffened. Huh et al. [24] designed a compressible tendon driven continuum manipulator, as shown in Fig. 4(f). With the Increase in internal force and the compression of consecutive soft joints, the variation in stiffness of robot body can reach up to approximately fifty times. The antagonism of hybrid actuation forces is also utilized. Maghooa et al. [28] and Stilli et al. [27] proposed continuum manipulators with hybrid actuation which incorporates tendons and pneumatics, as shown in Fig. 4(c) and (e). Stiffness of the manipulators can be changed continuously under the antagonism of actuation forces containing the tension of tendons and the inside air pressure.

In addition to regulating the antagonistic actuation, antagonism of robot's internal forces can also be adjusted by inserting external components with high elastic modulus. For example, when a flexible robot exhibits low stiffness, inserting an inner tube with a high elastic modulus can enhance robot's stiffness directly. The pulling force of the driving tendons and the elastic force of the inner tube antagonize each other when the robot bends, resulting in a high overall stiffness of the robot. Many methods of enhancing the stiffness of robot by inserting high elastic modulus components have been practiced. Lloyd et al. [33] designed a magnetic-actuated robot with variable stiffness, as shown in Fig. 4(g). The backbone of the robot is a sliding Nitinol rod. With the cooperation of different insertion length of the backbone and the application of magnetic field, stiffness of the robot can be varied. Li et al. [37] proposed a novel concentric

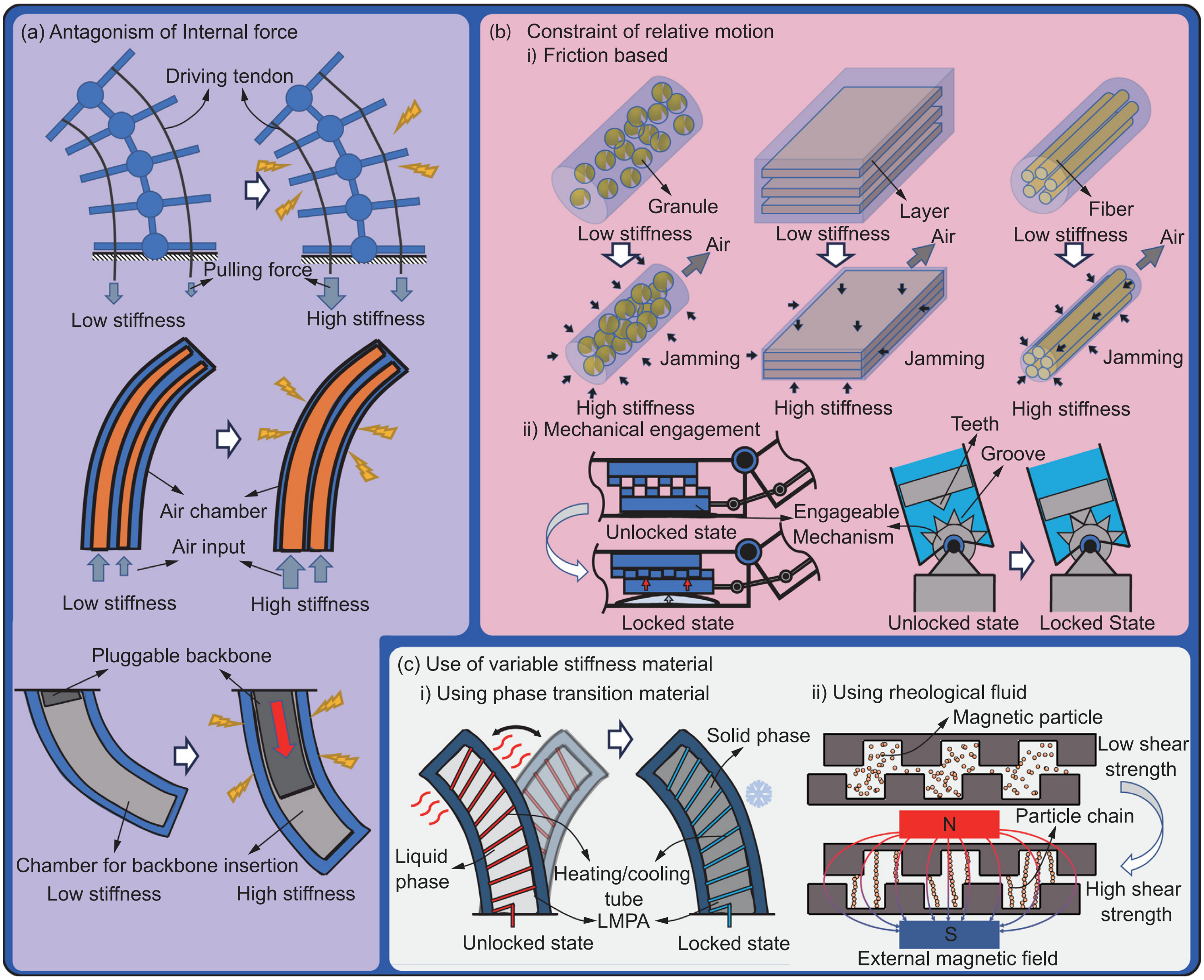


Fig. 3. Fundamental principles of varying stiffness of flexible robot. (a) Varying robot's stiffness by enhancing antagonism of internal force. (b) Varying robot's stiffness with constraint of relative motion, including friction-based method and mechanical-engagement-based method. (c) Varying robot's stiffness by using variable stiffness materials, including using phase transition materials and rheological fluids.

magnetic continuum robot with variable stiffness, as shown in Fig. 4(h). With changeable relative position of the inner and outer elastic tubes and the magnets, robot gains substantial stiffness variation which leads to different curvature bending. Wang et al. [36] designed a continuum robot with a sliding variable stiffness spine which bases on particle jamming, as shown in Fig. 4(i). After combining the particle jamming and spine growth, the robot enables reconfiguration of variable curvature and continuously changed stiffness.

Utilizing antagonism of internal force can enhance the stiffness of robot body simply, rapidly and continuously, without the need for complex structural design. However, this method still has some drawbacks. Firstly, it necessitates continuous energy input to sustain the high stiffness state of the robot, thereby increasing the control complexity of the robot. Additionally, antagonistic forces generated by different actuators or internal components exhibit strong coupling, amplifying the challenge of precise control. Furthermore, it lacks an ability to independently adjust the stiffness of partial robot sections, which limits its applicability in certain surgical scenarios.

2.2. Constraint of relative motion

In many designs of flexible robots, movable structures such as hinges and sliders are used, and the relative motion between the movable structures are strongly coupled with the robots' bending motions. Researchers have employed diverse methods to impede the deformation of robot and enhance stiffness by constraining the relative motion generated inside the movable structures, as shown in Fig. 3(b). And these motion constraint methods can be categorized into two groups based on increasing friction and mechanical engagement, respectively.

2.2.1. Friction-based constraint

Due to the couple between the relative motions of movable structures and the deformation of the robot, increasing the friction between these structures can enhance the robot's stiffness. Small objects like granular, fiber and layer are widely used to help enhance robot's stiffness, since there are numerous relative motions among these objects while robot deforming. A contractible enclosed membrane is placed outside the objects. When the membrane is relaxed, small objects inside can move freely along with the robot bending. After using pump extracting air inside the membrane, it contracts and all the objects would

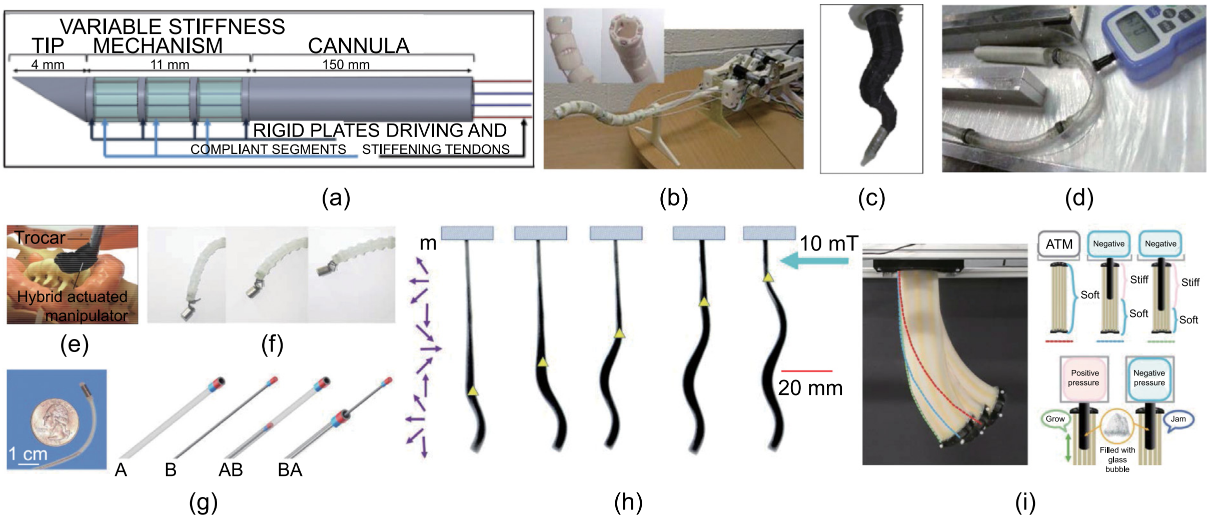


Fig. 4. Flexible surgical robot prototypes that vary stiffness by antagonism of internal forces. (a) Needle with variable stiffness that generated by different tendon tension [23]. (b) Flexible robot that can change stiffness continuously by varying tension of tendons with asymmetric links [9]. (c) Variable continuum robot with hybrid actuation [28]. (d) Intestine endoscope-like robot that vary stiffness with air chambers [29]. (e) Hybrid actuated surgical continuum robot with trocar [27]. (f) Continuum robot with compressible soft joints that adjust stiffness by tendon driving [24]. (g) Magnetic actuated continuum robot with insertable backbone [33]. (h) Magnetic actuated continuum robot with adjustable concentric structure [37]. (i) Continuum robot with variable stiffness insertable backbone, which changes stiffness by granular jamming [36].

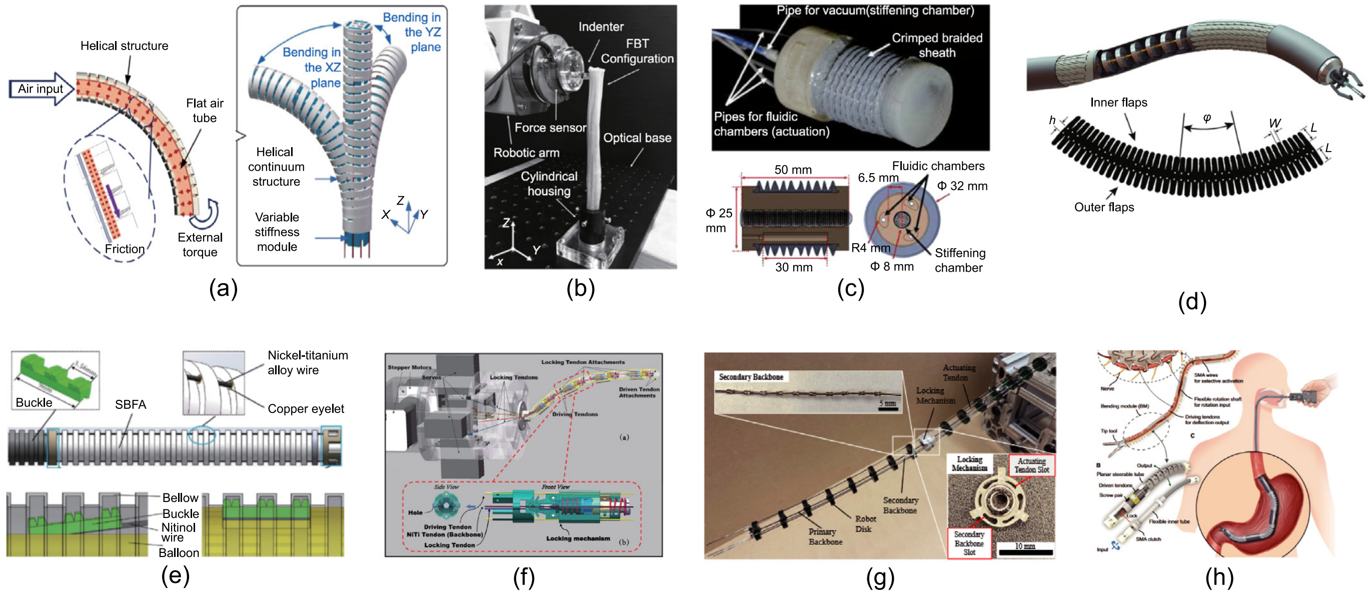


Fig. 5. Robot prototypes that vary stiffness based on constraining relative motion of internal movable structures. (a) Gastrointestinal endoscopy robot with rubber tubes inside to adjust its stiffness [38]. (b) Manipulator with variable stiffness based on fiber-jamming [41]. (c) One module of STIFF-FLOP robot, which stiffens the body by granular jamming [54]. (d) Manipulator with variable stiffness outer sheath based on layer-jamming [44]. (e) Continuum robot has engageable structures placed along the robot body [55]. (f) Modular lockable joint for flexible surgical robots, which can be (un)locked independently [59]. (g) Continuum robot with magnetic-actuated lockable mechanism [58]. (h) Continuum robot with lockable mechanism based on worm gears [81].

jam together under the atmospheric pressure. Friction between jamming objects would be significantly amplified, resulting in an overall increase in stiffness for the robot.

There are many examples of using friction-based methods to adjust robots' stiffness. Luo et al. [38] designed a flexible gastrointestinal endoscopy robot with tendon-driving and pneumatic hybrid actuation, as shown in Fig. 5(a). Four rubber tubes are placed symmetrically around the central axis of robot, which have relative slide motion respect to the robot body when robot bending. By injecting the air into tubes, the tubes expand and jam with the robot body to prevent it from changing shape, thereby achieving the shape locking of robot. Brancadoro et al. [41] proposed a manipulator prototype with variable stiffness by fiber jamming, as shown in Fig. 5(b). Through fiber jamming, the robot exhibits a large variation of stiffness along the radial direction while consistently maintaining high stiffness in the axial direction, which is well-suited for various endoscopic applications. Ranzani et al. [54] designed a pneumatic actuated soft flexible surgical robot with a stiffening chamber inside, as shown in Fig. 5(c). After air withdrawing from the stiffening chamber, small granules filled inside would jam together under the atmospheric pressure, and friction between the granules increases significantly, impeding the shape-changing of the robot body. Langer et al. [44] proposed a new type of outer sheath for flexible surgical robot which can be stiffened, as shown in Fig. 5(d). The layers on the outer sheath overlap with adjacent ones. When a vacuum is applied around the layers, high friction is generated due to the jamming of the overlapped parts, thereby reinforcing the robot's stiffness.

By amplifying the friction between internal movable structures, continuously adjustable stiffness of robot can be achieved, while the user should consider the continuous energy input of maintaining the high-stiffness state. What is more, many designs incorporate the creation of a vacuum around the movable structure, necessitating the use of a enclosed membrane and an air pump, which would increase the outer diameter of the robot and diminish the system's potential as being portable for more working scenarios.

2.2.2. Mechanical engagement (locking)

In addition to jam of small objects, engageable mechanisms are also used to lock robot's shape for varying stiffness. Relative movement occurs between the internal moveable parts of engageable mechanisms which is coupled with the deformation of robot body. Then the actuator drives the mechanism to engage, locking the shape of robot and increasing the overall stiffness. Comparing with other variable stiffness methods, engageable mechanisms can provide a more reliable shape locking, which depends on the utilized material.

Liu et al. [55] designed a reversible shape-locking mechanism which can be placed along the flexible robot, as shown in Fig. 5(e). The mechanism comprises buckles and bellows, which can engage together and lock the robot's shape under pneumatic actuation. Lin et al. [59] designed a modular lockable joint for flexible surgical robots, as shown in Fig. 5(f). With remote actuation by tendon driving, each joint can be locked and unlocked independently, and the joint's state can be maintained without continuous energy input, which provide robot more possible movements. Pogue et al. [58] proposed a novel magnetic locking mechanism for tendon-driven continuum robot, as shown in Fig. 5(g). Under the actuation of external magnetic field, a rotary plate inside the mechanism would rotate and engage with beads on the rope that pass through the mechanism, then the robot's shape is locked. Wang et al. [81] proposed a tendon-driven robot with lockable mechanism based on worm gear. Each joint has an individual SMA trigger to actuate locking motion, and robot can go inside human body to carry out surgeries with only one motor.

In addition to stable shape locking and a wider range of stiffness change, engageable mechanisms also have other advantages. Many mechanisms can maintain the engagement individually, which reduces the coupling between stiffness adjustment and robot actuation, allowing for a wider range of robot movements and expanding the workspace. Clark et al. [82] researched the working modes of a flexible robot with shape-locking mechanism, showed that the proposed robot can not only mimic the working modes of typical robot arms, such as PUMA, SCARA, and SPHERICAL, but also work as a general articulated one. Wockenfußet al. [83] designed a continuum robot with pneumatic shape-locking mechanism, and used only two motors to drive it bending in complex shapes with large workspace.

However, the locking state of engageable mechanism is limited to either locked or unlocked and continuous stiffness adjustment cannot be achieved. Additionally, many mechanisms possess complex structures that are challenging to miniaturize for small scale flexible robots. Moreover, they may require bulky external driving modules, such as motors and air pumps, which increases the complexity and footprint of robot system.

2.3. Use of variable stiffness materials

Numerous materials can change phase easily under external stimuli. Taking the wax as an example, it is solid at room temperature and will become liquid after being heated above the melting point. Therefore, many researchers change the stiffness of flexible robots by implanting these materials into robot body and altering their physical properties through applying external stimuli, as shown in Fig. 3(c). Commonly used variable stiffness materials can be categorized into two groups as phase-transition material and rheological material.

2.3.1. Phase transition materials

Phase transition materials, such as low-melting-point alloy (LMPA) and shape-memory-alloy (SMA), can change its stiffness with joule heat input, which are widely integrated into the robot to enable stiffness adjustment. There are many low-cost phase transition materials with different properties, such as wax and shape memory nickel titanium alloy, on the market, which provide researchers diverse choice. Since these materials can provide considerable stiffness variation, they can be applied to flexible surgical robots with small outer diameters, such as catheter robots.

Kim et al. [75] designed a novel flexible robot for MRI-guided neurosurgery, as shown in Fig. 6(a). The robot's body is composed of consecutive SMA springs. The SMA spring exists in austenite phase in high temperature, leading to a low stiffness of robot body. When heat dissipates and temperature of SMA springs drops, they transform to martensite phase and become harder, resulting in a high stiffness of robot body. Wang et al. [61] proposed a controllable stiffness manipulation arm with phase-change material filling inside the gap of joints, as shown in Fig. 6(b). With a large area rolling electric heating film and water cooling system, the phase-change material can switching between liquid and solid phases to meet different stiffness needs. Piskarev et al. [72] proposed a magnetic catheter with a variable stiffness outer tube made of shape memory polymer PTFE(polytetrafluoroethylene), as shown in Fig. 6(c). The fabrication process of PTFE tube contains repeat dipping and curing, which allows the tube to be thin for the neurosurgery. Internal helical copper electrode can heat the tube, causing it to soften and allowing the robot to be flexible. Meanwhile, the hollow backbone can serve as a cooling channel to dissipate heat from the tube, thereby stiffening the robot. Le et al. [12] designed a continuum robot with four PET tubes inside, as shown in Fig. 6(d). Each tube has a flexible stainless steel sheath embedded in it to work as a heating element, which help the tube transform from stiff glass state to soft rubbery state to vary robot's stiffness. And cooling air goes through the channel of PET tube to actively and safely remove the heat for making robot stiff again. Farshid et al. [66] designed a two-segment continuum robot with spring embedded as elastic backbone, as shown in Fig. 6(e). The spring has been coated with PTFE, and multiple sets of electrical wires are placed inside to control the location of being soft.

However, some factors of using these materials should be considered. Heat is needed for these materials when changing their stiffness, and the temperature of material may be higher than 41 °C, which is the threshold of scald of human body. What is more, the heating and heat dissipation process takes from 10 s to several hundred seconds, which is not suitable for adjusting the stiffness of robot frequently during surgery. Therefore, in addition to the compact heating system, a heat dissipation system is also required, which is critical to improving the working efficiency of the robot, while it also increases the complexity of the robot design and poses a challenge to the miniaturization of the robot system.

2.3.2. Rheological fluids

Rheological fluids can adjust their viscosity in response to corresponding stimuli, exhibiting characteristics including fast response, significant viscosity changes, and great bio-compatibility

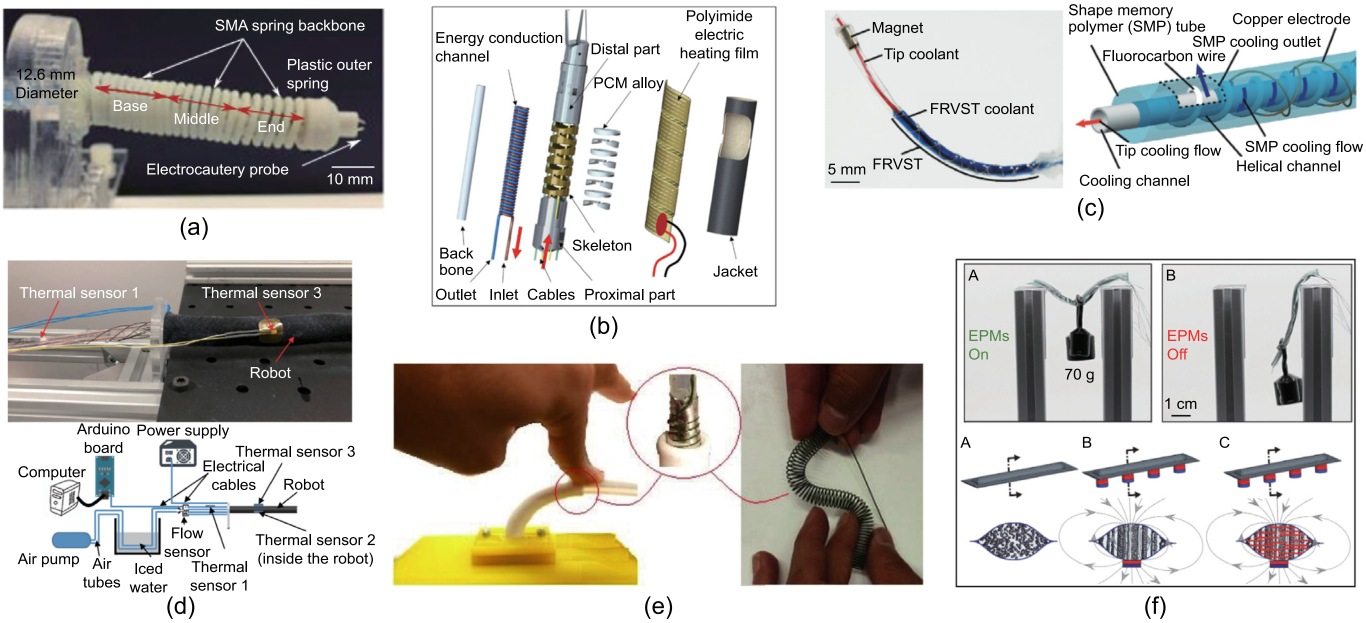


Fig. 6. Robot prototypes that vary stiffness by using variable stiffness materials and modifying robot structure directly. (a) A continuum robot that consists of consecutive SMA springs [75]. (b) A surgical manipulator arm with LMPA employed inside [61]. (c) A magnetic catheter robot using LMPA to change body's stiffness [72]. (d) A variable stiffness continuum robot composed of four PET tubes [12]. (e) A variable stiffness spring-based continuum robot with PTFE coating outside [66]. (f) A soft robot with variable stiffness by integrating with magneto-rheological fluid and layer jamming [76].

Table 2
Anatomical constraint of common natural tracts.

Position	Outer diameter requirement	Reference
Cochlea	<2 mm	[84]
Nasal middle meatus	<1.69 mm	[85]
Nasal inferior meatus	<5–8 mm	[86]
Radial Artery	<1.5–4 mm	[87]
Superior vena cava	<8–15 mm	[88]
Esophagus	<15 mm	[89]
Urethra	<3.25 mm	[90]
Choledocho	<3.1–3.4 mm	[91]
Fallopian	<5–12 mm	[92]
Vagina	<25–35 mm	[93]
Cervix	<33 mm	[94]
Duodenum	<7.5–12.1 mm	[91]
Colon	<11–15 mm	[91]

[77], which endows rheological fluids with great potential in varying stiffness. Inside the fluid there are abundant tiny particles, which can be arranged as chain structures under the external stimulus field, and then the shear force perpendicular to the chain is increased owing to the interaction forces between the particles, which can be used to impede the deformation of flexible robot.

Gaeta et al. [76] designed a soft robot with variable stiffness by combining magneto-rheological fluid and particle jamming, as shown in Fig. 6(g). With the application of an external magnetic field, particles in the magneto-rheological fluid align in chains and cling to the layers inside the robot. The shear force of the fluid increases, resulting in an enhancement of friction between layers, leading to an improved jamming effect and effectively altering the stiffness of the robot.

However, the application of rheological fluids to control the stiffness of flexible surgical robots is researched little, and there are many issues should be considered. In order to produce considerable changes in the viscosity of the rheological material inside surgical robots, the intensity of the external excitation field and the volume of the rheological material are needed to be enlarged [95]. What is more, a suitable excitation device also needs to be proposed so that the fluids can be well excited even in a narrow surgical environment. Therefore, how to balance the performance of materials and the volume of robot needs to be considered. Progress of feasible designs and stronger rheological materials will help the development of variable stiffness flexible surgical robots.

3. Challenges and perspectives

In this section, challenges of current variable stiffness methods are summarized, and two potential variable stiffness method are introduced. Moreover, the advantages of variable stiffness flexible robots in avoiding obstacles and following predetermined paths are discussed.

3.1. Challenges of current variable stiffness methods

Although methods summarized previously can enable the stiffness variation of flexible MIS robots, they still exhibit several inevitable drawbacks. Due to the coupling between actuation forces, utilizing antagonism of internal force to vary stiffness increases the complexity of precise control for robotic operations, which would escalate as the number of controllable section increases. Altering the stiffness of a robot by constraining motions of internal movable structures, the complexity of these structures limits their capability of miniaturization. And the engageable mechanisms only have two states, locked and unlocked, resulting in their inability to provide continuous change stiffness.

Using variable stiffness materials also encounters problems. Robots vary stiffness basing on thermally phase transition materials cannot alter their stiffness frequently, since the materials need time to be soften and stiffen. And the phase transition points of many materials are higher than the scald threshold of the human body, which increases the risk of surgery. For rheological fluids, altering stiffness requires a good balance between the intensity of external field and the volume of fluids, and how to remotely activate the rheological effect of these fluids to vary the stiffness of a millimeter-level flexible robot deep inside the human body remains a challenge.

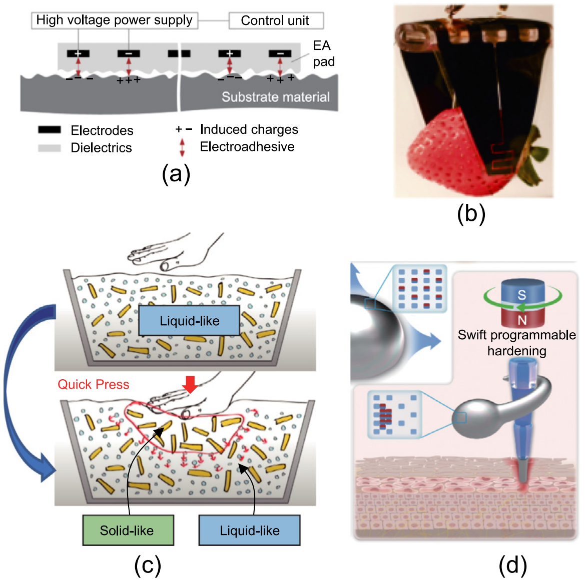
Table 3
Characteristics of flexible robots using common variable stiffness methods.

Principle	Outer diameter	Stiffness adjusting ratio	Response time	Brief description	Reference
Modifying robot's structure	10 mm	–	Fast	Plugging a Nitinol backbone into robot	[33]
Stiffness variable material	15 mm	23.9–25.1 times	≈20 s	A starch-based bio-compatible thermoplastic is used in robot	[11]
Friction based	18 mm	3.24 times	<3 s	Jamming of internal chambers and robot body	[38]
Friction based	24 mm	11.5 times	Fast	Using layer jamming	[39]
Internal force	20 mm	2.19 times	Fast	Stiffness adjusting by changing tension of tendons	[96]
Stiffness variable material	2.3 mm	21 times	18 s for heating, 107 s for cooling	Conductive phase-change polymer is used in robot	[60]
Stiffness variable material	16 mm	1.39 times	Fast	A SMA-based variable stiffness sheath is designed	[14]
Stiffness variable material	12.6 mm	–	80 s for heating, 220 s for cooling	Variable stiffness SMA springs are used to composed robot body	[75]
Modifying robot's structure	–	–	Fast	Elastic backbone tunes robot's stiffness with different insertions	[34]
Friction based	7 mm	–	Fast	Using minimal actuator to impede each joint rotating independently	[40]
Stiffness variable material	8.5 mm	8–9.3 times	25 s for heating, 5 s for cooling	Phase-change material is used in manipulator's joint	[61]
Stiffness variable material	17 mm	1.63 times	17 s for heating, 18 s for cooling	LMPA is used in the endoscopic-like robot	[62]
Friction based	16 mm	5.14 times	Fast	Fiber jamming is used to vary stiffness of continuum robot	[41]
Stiffness variable material	7 mm	36.28 times	9.2 s for heating, 15.4 s for cooling	LMAP is used in manipulator	[63]
Modifying robot's structure	8 mm	6.4 times	Fast	Elastic backbone tunes robot's stiffness with different insertions	[35]
Stiffness variable material	2.33 mm	–	15 s for heating, 20 s for cooling	LMPA is used in the magnetic continuum robot	[64]
Friction based	35 mm	1.36 times	Fast	Granular jamming is used to vary stiffness of continuum robot	[42]
Friction based	14.5 mm	3.78 times	Fast	Fiber jamming is used to vary stiffness of continuum robot	[43]
Rheological fluid	13 mm	3.44 times	Fast	Magneto-rheological fluid is used in the robot to vary its stiffness	[12]
Stiffness variable material	15 mm	22 times	30 s for heating, 11.3 s for cooling	Variable stiffness thermoplastic tube is used in the robot	[12]
Mechanical engagement	13 mm	3.2 times	Fast	Hydraulic actuated lockable mechanism is used to lock robot's shape	[55]
Stiffness variable material	13 mm	–	8.2 s for heating, 58 s for cooling	Phase-change alloy is used in continuum manipulator	[66]
Stiffness variable material	43 mm	3.0 times	60 s for heating, 100 s for cooling	LMPA is used in flexible manipulator	[67]
Friction based	13 mm	24 times	Fast	Jamming-based stiffening sheath is used for robot	[44]
Stiffness variable material	5 mm	5 times	–	Shape memory polymer tube is sued in the robot	[68]
Internal force	2.3 mm	9 times	Fast	Varying robot's stiffness by changing tension of tendons	[23]
Friction based	5.5 mm	–	Fast	Cable jamming actuated by hydraulic system is used to vary robot's stiffness	[45]
Variable stiffness material	12 mm	1.18 times	8 s for heating, 80–100 s for cooling	Thermalplastic is used in the robot to vary stiffness	[69]
Friction based	20 mm	7.5 times	Fast	Granular-jamming is implemented to vary robot's stiffness	[46]
Variable stiffness material	2.5 mm	–	10 s for heating	LMPA is used in flexible catheter	[70]
Friction based	15 mm	–	Fast	Granular-jamming is used in the robot to vary stiffness	[47]
Modifying structure	3 mm	–	Fast	Rearrange relative positions of inner and outer tube to vary stiffness of robot	[51]
Mechanical engagement	16 mm	–	Fast	Lockable slider mechanism is used to lock robot's shape	[57]
Mechanical engagement	10.5 mm	–	Fast	Novel magnet-actuated lockable mechanism and bead rob are used to lock robot	[58]
Modifying structure	10 mm	2.5 times	Fast	Granular-jamming based insertable backbone is used to change stiffness of robot	[36]
Friction based	60 mm	4.85 times	Fast	Varying stiffness by changing tension of tendons with different patterns	[32]
Friction based	–	8.5 times	–	Stiffness variation is induced by the friction change caused by electrostatic adsorption	[51]

(*continued on next page*)

Table 3 (*continued*).

Friction based	86 mm	3.13 times	Fast	Layer-jamming is used to var stiffness of robot	[52]
Stiffness variable material	1 mm	5.8 times	10 s for heating, 17 s for cooling	Phase-change alloy is used in submillimeter catheter for varying stiffness	[51]



(a) (b) (c) (d)

Fig. 7. Principles and examples of varying stiffness by using electrostatic adhesion (EA) and non-Newton fluid (NNF). (a) The concept diagram of Johnsen–Rahbek effect [97]. (b) A soft gripper using EA force to adhesive and grab objects, proposed by Shintake et al. [98]. (c) The concept diagram of principle of stiffness variation of NNF. (d) A magnetic actuated soft robot with variable stiffness by using NNF [99].

According to the above summary of drawbacks and the working requirements, characteristics of ideal variable stiffness method can be concluded as below:

- Have good bio-compatibility
- Vary stiffness rapidly and reversely
- Have continuous and large variation in stiffness
- Need only small volume
- Enable localized stiffness variation
- Decouple stiffness variation process from other robot actions

From the perspective of safety, the size of robot is a crucial parameter that should be considered, then a summary of constraint of common natural tracts is given out in Table 2, which can be a reference for designers to determine the maximum size of their flexible robots. Furthermore, two potential methods that can be used to vary the stiffness of flexible MIS robots are introduced in the following section, which are employing electrostatic adhesion (EA) and non-Newton fluid (NNF), respectively. Variable stiffness mechanisms based on these two methods have capability to reach those ideal characteristics mentioned above.

3.2. Potential variable stiffness methods

3.2.1. Electrostatic adhesion

EA is a widely used method in robotics for adhesion application [97]. The EA force, generated from the Johnsen–Rahbek (J–R) effect, exist between a conductor and a semiconductor when they are in contact and a voltage is applied across them, as shown in Fig. 7(a).

EA has great potential in varying stiffness of flexible surgical robot, as it can impede the relative motion of robot's structure by adhering the movable parts and increase the friction [100]. In addition, EA only actuated by applying voltage on the electrodes rather than tendon driving or air pumping, which can decouple the stiffness variation process with actuation of robot bending, as shown in the example in Fig. 7(b). And the actuation module of EA based mechanism only contains a electric power and relative circuit board. Comparing with the common actuation module that contains a large amount of motors or bulky fluid pump, the actuation module of EA only contains electric power and circuit boards, which is small and portable for more possible surgical scenarios like outdoor emergency surgery.

However, some challenges may occurred when applying EA on the flexible surgical robots. The magnitude of EA force is relative to not only the type and thickness of the material of electrode, but also the voltage and contacting area [101]. Therefore, in order to achieve excellent stiffness variation capability in millimeter-level surgical robots, electrodes with higher dielectric constant should be invented, and the effective contacting area of electrodes within the robot body should be enlarged.

3.2.2. Non-Newtonian fluid

Non-Newtonian fluid also has great potential to be used in the small-scale variable stiffness surgical robots, whose viscosity depends on the stress on it and does not follow the Newton's law of viscosity [102], as shown in Fig. 7(c).

Some kinds of NNFs shows the characteristic that their viscosity has a positive relationship with the shear rate of itself. With quickly oscillating external stimuli, these NNFs can rapidly transition from fluid to solid states, as the jamming of inner tiny particles, which can be used to vary stiffness of flexible robots. Xu et al. [99] proposed a novel design of magnetic miniature soft robot with variable stiffness that base on the NNF, as shown in Fig. 7(d). A rapidly oscillating external magnetic field is applied to the robot, and the stiffness of NNF-based robot body is changed, as the inner particles are resisting the intense interactions.

The exploration of NNF-based variable stiffness mechanisms requires further investigation in the future, and the development of novel NNFs with significant stiffness variation is required.

3.3. Advantages of variable stiffness flexible robots in motion

With certain stiffness varying methods, flexible robots can independently lock parts of the body and keep moving the free parts, which can achieve novel motions that differentiate them from previous flexible robots. The control strategy for flexible robots moving in these type motions has not been extensively investigated, which presents the potential for these robots to achieve more precise path-following and enhanced obstacle-avoidance capabilities [83,103]. The follow-the-leader (FTL) is the best moving strategy for flexible robot to follow a predetermined path and avoid obstacles [104]. However, FTL necessitates the robot to independently and simultaneously control each movable part, which is hard to be attained for hyper-redundant flexible surgical robots.

By endowing each section of the robot with independent locking capabilities, the flexible robots can follow a predetermined path with minimal error by only a small number of actuators, as shown in Fig. 8. Considering a scenario that two tendons are attached to the distal end of a planar flexible robot to control its bending motion. Without any lockable mechanism, the robot can only attain C-shaped configurations that open on both sides. After

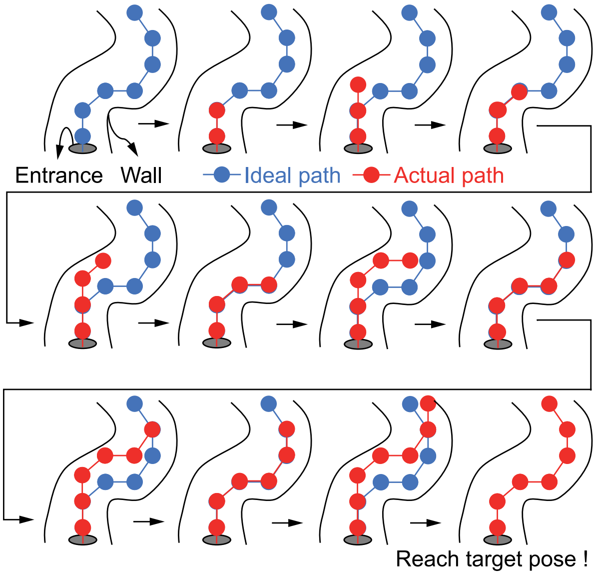


Fig. 8. A flexible robot with independent lockable joints can follow a predetermined path with multiple advancing steps.

equipping each joint with an independent lockable mechanism, the robot can be selectively actuated to rotate only a few joints while keeping others locked, thereby achieving more complex configurations. By unlocking and accurately rotating only one joint in each movement, and incrementally advancing the entire system forwardly step by step, the robot can follow a predetermined path with minimal error. The magnitude of path-following error depends on the size of each step.

With this motion strategy actuated by only few motors, the robot can perform remarkable flexibility and be in small size simultaneously. It holds great potential for developing applications of variable stiffness flexible robots in surgery [105,106], manufacturing [107], rescue operations [108], aerospace tasks [109], and etc.

4. Conclusion

In this review, variable stiffness methods from relative literature have been categorized into three types based on their fundamental principles: antagonism of internal force, constraint of relative motion, and using variable stiffness materials. Each method is elucidated along with applications, its advantages and drawbacks are summarized. The characteristics of ideal variable stiffness method are proposed, and two potential methods are introduced. Furthermore, the advantages of variable stiffness flexible robot in motion are discussed, which may lead to expanded exploration of applications of variable stiffness flexible robots in rescue, manufacturing, outdoor surgery, aerospace, and other fields.

CRediT authorship contribution statement

Botao Lin: Investigation, Writing – original draft. **Shuang Song:** Data curation, Project administration, Validation. **Jiaole Wang:** Conceptualization, Funding acquisition, Investigation, Project administration, Supervision, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was supported in part by Talent Recruitment Project of Guangdong (2021QN02Y839), and in part by the Science Technology Innovation Committee of Shenzhen (JCYJ20220818102408018 and GXWD20231129103418001).

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