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REVIEW

Principles and methods for stiffness modulation in soft robot design and development

Yang Yang[1,2] · Yingtian Li[2] · Yonghua Chen[2]

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Abstract
Compared to traditional rigid robots, soft robots, primarily made of deformable, or less rigid materials, have good adaptability, conformability and safety in interacting with the environment. Although soft robots have shown great potentials for extended applications and possibilities that are impossible or difficult for rigid body robots, it is of great importance for them to have the capability of controllable stiffness modulation. Stiffness modulation allows soft robots to have reversible change between the compliant, or flexible state and the rigid state. In this paper, we summarize existing principles and methods for stiffness modulation in soft robotic development and divide them into four groups based on their working principles. Acoustic-based methods have been proposed as the potential fifth group in stiffness modulation of soft robots. Initial design proposals based on the proposed acoustic method are presented, and challenges in further development are highlighted.

Keywords Variable stiffness · Stiffness modulation · Soft robots · Acoustics · Ultrasonic

Abbreviations

SMP	Shape memory polymer
SMA	Shape memory alloy
LMPA	Low melting point alloy
ERF	Electro-rheological fluid
MRF	Magneto-rheological fluid
MIS	Minimally invasive surgery
DEA	Dielectric elastomer actuator
PLA	Polylactic acid
ABS	Acrylonitrile butadiene styrene

Introduction

Conventional rigid-bodied robots have good performance in industries benefitted from their high positioning accuracy, precise motion control and large force output [1]. However, in other scenarios such as unstructured environment, or interaction with human, rigid-bodied robots perform poorly due to the lack of compliance, elasticity and safety. The emergence of soft robots has pushed the boundaries of robotics research by composing the robots with less or non-rigid materials, thus enabling the robots with capabilities to undergo large deformation when interacting with environment [2–4].

Even though soft robots have gained a lot of research interest in the robotics field, they are still faced with challenges that need to be addressed before their widespread applications [5]. One challenge for soft robots is the ability to modulate their stiffness to adapt to different application scenarios. Low stiffness endows the soft robots with adaptability and conformability to the environment, while high stiffness is needed to transmit force and to bear load. Therefore, the ability to modulate or control stiffness is highly expected in soft robots. So far, the soft robotics research community has reported significant progress on stiffness modulation based on different techniques [6]. However, it is still not possible to achieve a combination of large stiffness variation ratio, fast response and energy efficiency from one single technique. When choosing a technique for stiffness modulation, there is always a trade-off among several considering factors. As such, it is high time to look back and conduct a review to summarize the existing research outcomes. What's more, we will also present a possible alternative for stiffness modulation in soft robotic design and development.

✉ Yonghua Chen
yhchen@hku.hk

1 College of Information Engineering, Shenzhen University, Shenzhen, China

2 Department of Mechanical Engineering, The University of Hong Kong, Pokfulam Road, Pokfulam, Hong Kong, China

Table 1 Summary of stiffness modulation methods for soft robots

Stiffness modulation methods	Type of control	Principle	Materials/composing parts	Robotic applications
Glass/phase transition-based methods	Thermal energy	Glass transition, phase transition	Thermoplastics, SMP, SMA, LMPA, Wax	Gripper [13], robotic origami [15], legged robot [22] and load bearing functional part [16,23]
Viscosity-based methods	Electric/magnetic field	Viscosity change	ERF, MRF, electroactive gel	Gripper [28] and fluidic actuator [30]
Jamming-based methods	Pressure	Interparticle friction, interlayer friction	Particles, layers	Gripper [33], rolling robot [37] and surgical robot [39]
Structure-based methods	Motor/pressure	Geometry or friction variation	Tendons, fluidic actuators	Continuum manipulator [41] and snake-like robot [42]
Acoustic-based methods	Frequency	Acoustic field variation	Transducers, particles, non-Newtonian liquids	To be identified

The capability of stiffness modulation is found important for damping structures [7], morphing structures [8], medical devices [9] and also compliant actuators for rigid-bodied robots [10]. In this review, we only focus on stiffness modulation methods in soft robotic design and development. Previous research on this topic is reviewed in second section, and prospects for future research on stiffness modulation are proposed in third section, followed by conclusions in fourth section.

Stiffness modulation methods

In previous research, various stiffness modulation methods have been reported in the literature and a number of classifications of such methods have been proposed in previous reviews such as actuation or energy [6], mechanical properties of material [7], and factors influencing the flexural stiffness (for medical devices) [9]. In this review, we divide existing stiffness modulation methods used by soft robots into four subgroups depending on their stiffness tuning principles and propose acoustic-based stiffness tuning as a potential principle for future stiffness modulation research. A summary of stiffness modulation methods for soft robots is shown in Table 1.

Glass/phase transition-based methods

Among the stiffness modulation strategies for soft robots, material glass transition or phase transition-based methods are widely used. Mechanical properties of thermoplastics would undergo variation during thermal transitions including glass transition (T_g) and melting transition (T_m). Elastic modulus of thermoplastics changes dramatically when heated to around its glass transition temperature (T_g). Similar phenomenon is also found in shape memory polymers (SMPs). Figure 1a illustrates the change of SMP's elastic modulus with temperature change [11]. Below T_g, SMP is at 'glassy' hard phase with high elastic modulus. Above T_g, SMP transforms to 'rubbery' soft phase that can be easily deformed. The modulus ratio between glass and rubber states of SMP can be as high as several hundred. The glass transition region of SMPs provides an opportunity for stiffness modulation. Yang et al. reported variable stiffness ball joints whose stiffness was tuned by thermal stimulus (low stiffness above T_g and high stiffness below T_g) and cascaded a number of these joints to form a hyper-redundant robotic arm [12]. The ball joint is made of two materials: ABS and SMP. When heated above T_g, the joint exhibits low resistive torque and can move freely because SMP is at rubber state. When cooled down below T_g, SMP is at glass state and the joint's resistive torque increases dramatically. In this way, the ball joint's stiffness is modulated. The whole hyper-redundant arm could be printed with a consumer-grade 3D printer. In their subsequent research, variable stiffness soft fingers were developed using SMP for stiffness tuning and bending shape control [13,14]. They attempted heating SMP materials with integrated pin heaters [13] and with conductive elastomers [14]. The main novelty of using conductive elastomers was that they could not only provide Joule heating for the SMP part but also enable the finger joint with position feedback capability. A schematic of this robotic finger design is provided in Fig. 1b [14]. Its design is inspired by the human index finger. The three bending joints are realized by heating SMP material above T_g at the joint regions. As a result, the finger would bend at low stiffness joints when pressurized air flows in the air chamber. Except for soft pneumatic fingers, SMP has also been applied in tendon-driven under-actuated robotic origamis for stiffness control [15].

Thermoplastics have been used for developing multifunctional robotic fibers to mimic the capabilities of human

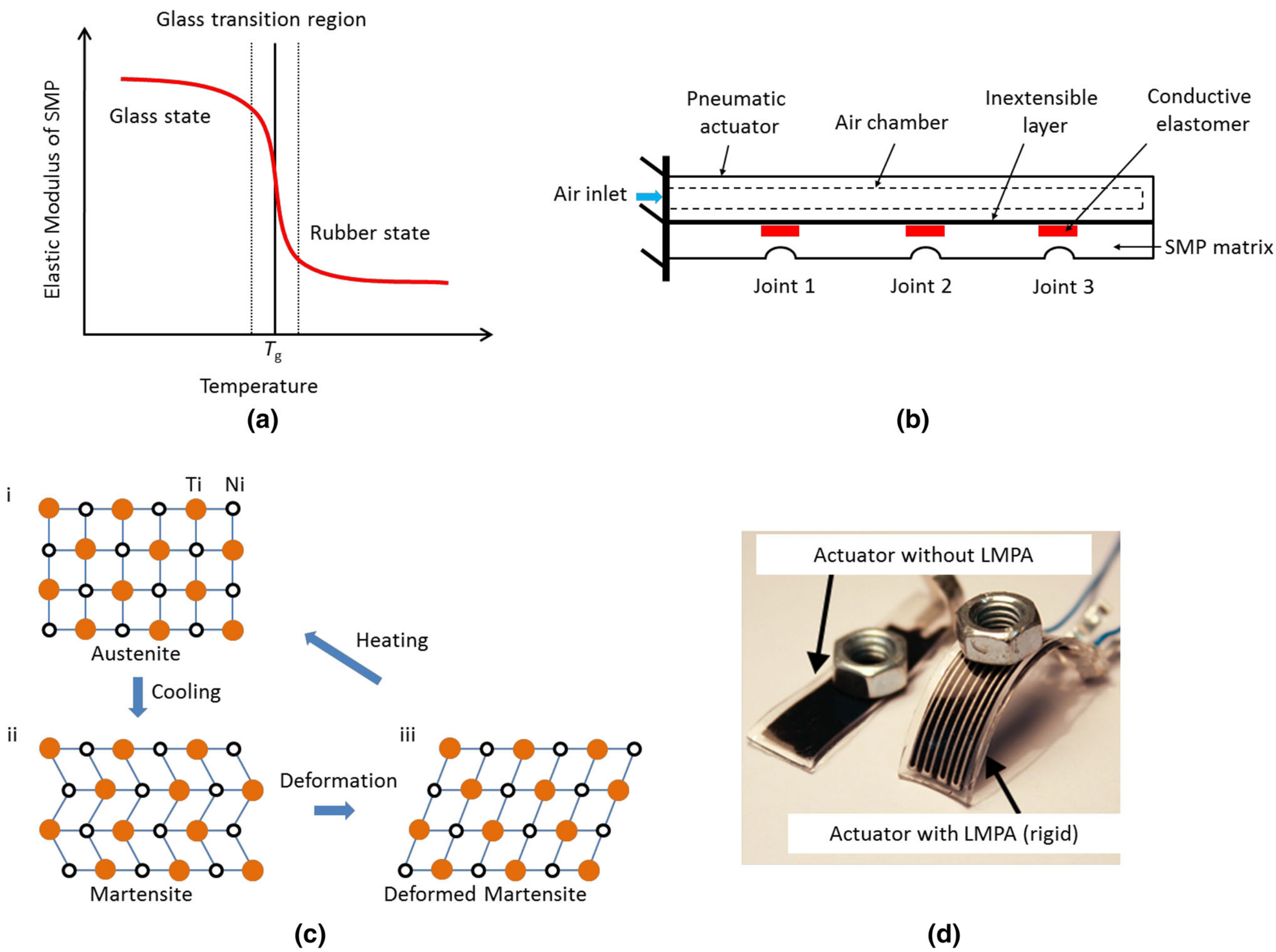

Fig. 1 Phase transition-based variable stiffness methods. **a** SMP's elastic modulus change with temperature [11]. **b** A variable stiffness soft finger based on SMP and conductive elastomer [14]. **c** Phase transition in Ni-Ti SMA [17]. **d** LMPA applied in DEA-based soft actuator for stiffness modulation [20]

muscle fibers in a research conducted by Yuen et al. [16]. In their research, the glass transition in PLA ($T_g = 55 - 65\,°C$) or ABS ($T_g = 105\,°C$) was tapped for stiffness modulation and thus the long-time lifting of a soft robotic arm was accomplished without continued energy input. For the fiber design, PLA or ABS materials encapsulated a Ni-Ti wire (a kind of SMA) in the core to provide thermal heating needed for stiffness modulation. When connected to electrical energy, the SMA wire provides not only thermal energy, but also serves as the actuator.

Except for thermoplastics and SMPs, SMAs also exhibit modulus variation when transforming from austenite to martensite through variation of thermal energy. Diagram showing the phase transition of Ni-Ti-based SMA is presented in Fig. 1c [17]. However, the ratio of elastic modulus change of SMAs is relative small ($< 4x$) and its absolute modulus is still high (83 GPa as austenite [18]), which limits SMAs' application for stiffness modulation in soft robots. Currently, SMAs are mostly used for actuation for soft robots by utilizing their shape memory effect.

Low melting point alloys (LMPAs) are emerging for variable stiffness applications recently since a large stiffness range can be achieved when LMPAs changing between solid and liquid states. Schubert et al. developed a variable stiffness composite with LMPA (47 °C melting temperature) microchannels encapsulated by soft poly (dimethylsiloxane) (PDMS) [19]. The composite demonstrated stiffness change of 25 folds from 40 to 1.5 MPa when LMPA was heated from solid state to liquid state. Moreover, the composite possessed inherent strain sensing capability by monitoring its resistance change since LMPAs were also electrical conductors. Using this composite, variable stiffness actuators have been developed by using dielectric elastomers actuators (DEA) and a LMPA substrate as stiffness tuning module as shown in Fig. 1d [20]. Hao et al. [21] also demonstrated variable stiffness soft robotic grippers based upon soft pneumatic actuators and LMPA. Aside from grippers, LMPA is applied in multi-legged robots and the stiffness modulation capability enables the robot with leg morphology change to adapt to different applications such as climbing

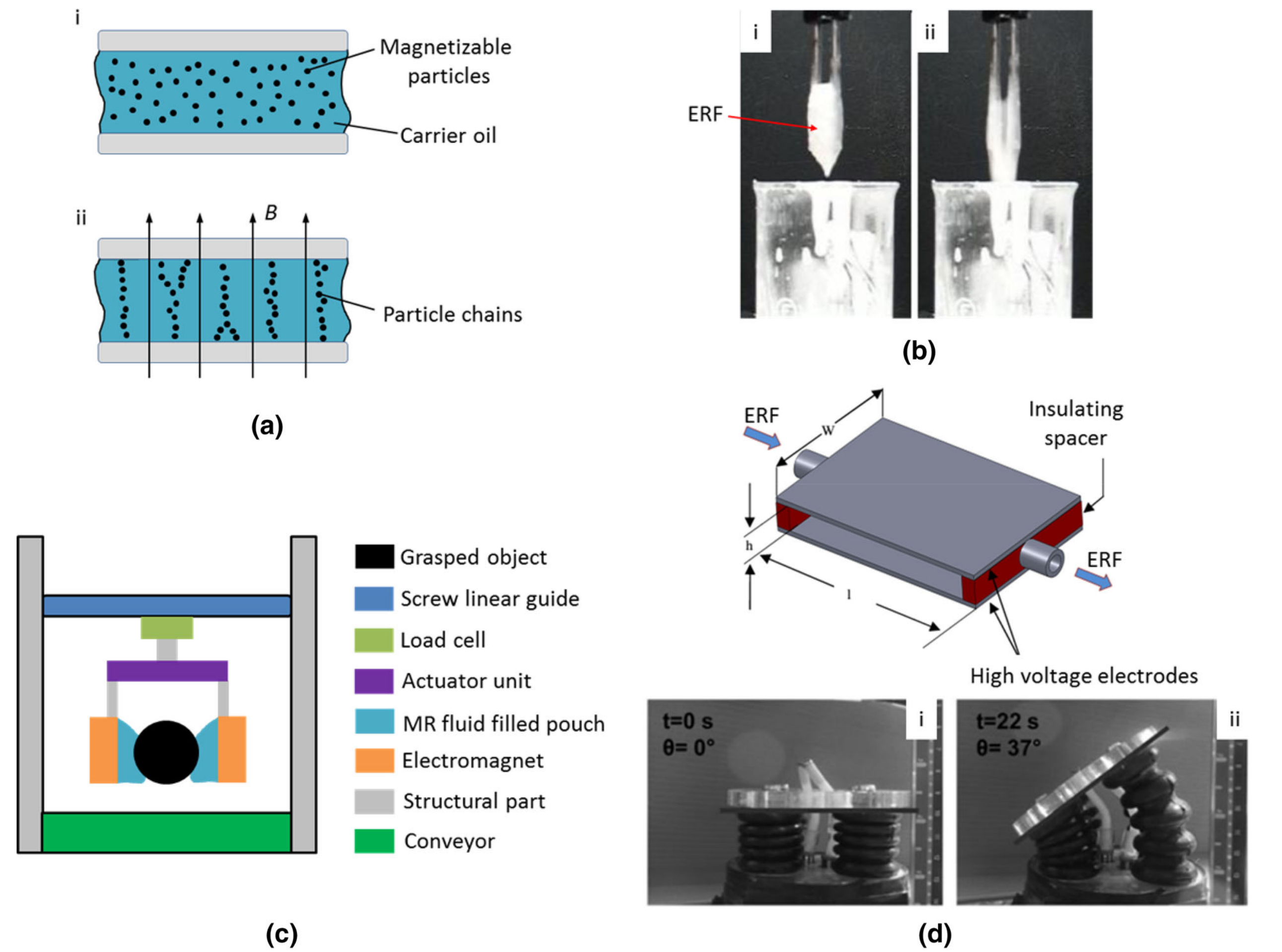

Fig. 2 Viscosity-based stiffness modulation methods. **a** Principle of MR fluids. *i* MR suspensions. *ii* Chain formation of magnetizable particles under magnetic field. **b** ER fluids at different states. *i* Gel state with high viscosity when electric field is applied. *ii* Liquid state with low viscosity when no electric field is applied [27]. **c** A universal gripper using MR fluids to realize passive shape adaption. Stiffness modulation is achieved by controlling applied magnetic field [28]. **d** Innovative soft robot design with ER fluids. Upper panel: an ER valve controls the flow of ER fluids through it by controlling the applied voltage [27]. Lower panel: flexible fluidic actuator system utilizing ER valves for actuation and control. *i* The system at its original state. *ii* The system undergoes bending movement by selectively actuates the flexible fluidic actuators [30]

a ladder [22]. Wax as another low melting temperature material is also used as a candidate for stiffness modulation in soft robotic applications. Researchers have investigated wax-coated polyurethane foam composite with thermally tunable stiffness [23]. The composite exhibited not only variable stiffness function but also self-healing property.

Viscosity-based methods

Magneto-rheological (MR)/electro-rheological (ER) fluids, elastomers and networks are another important group of functional materials which are utilized for stiffness modulation in soft robot development. The stiffness modulation of MR fluids and ER fluids is based on the principle that viscosity and yield stress of such fluids will change as the change of applied magnetic field or electric field [24,25]. Diagram showing microstructures of MR fluids without and with the presence of magnetic field is shown in Fig. 2a [26]. When magnetic field is applied, magnetizable particles in carrier oil form a chain in the direction of magnetic flux and thus the viscosity and shear modulus of the fluid changes accordingly. Same phenomenon is also found in ER fluids which contain electrically active particles instead of magnetizable particles used in MR fluids. ER fluids change from high-viscosity gel state to low-viscosity liquid state with and without applied electric field, which is presented in Fig. 2b [27].

The tunable viscosity of MR fluids has inspired researchers to use this property in soft robotic development for applications where passive adaption and delicate grasping are preferred. One application is in food industry where deli-

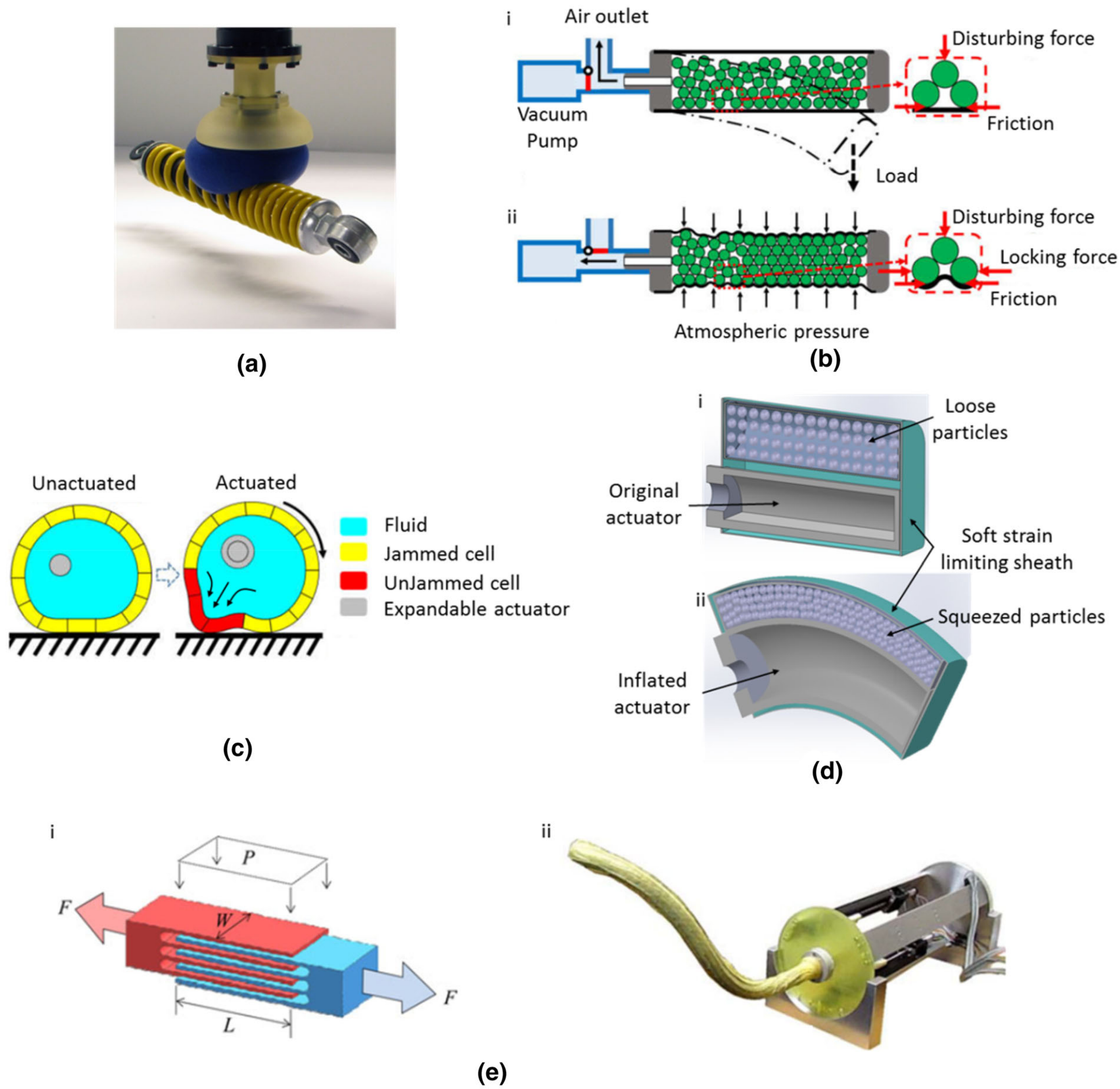

Fig. 3 Jamming-based stiffness modulation methods. **a** A particle jamming-based universal gripper picking up a shock absorber coil [33]. **b** Schematic of particle jamming [34]. **c** Locomotion realized by selectively controlling the jammed and unjammed cells of the soft robot skin [37]. **d** Diagram of the soft actuator endowed with passive particle jamming. *i* Soft actuator at its original state. *ii* Soft actuator is deformed by compressed air and is also stiffened by passively jammed particles [38]. **e** A layer jamming-based continuum manipulator for MIS. *i* Diagram of layer jamming element. *ii* The manipulator prototype [39]

cate food products with varying shapes can be handled by a MR fluid gripper [28]. Schematic of the gripper design is shown in Fig. 2c. During grasping operation, MRF is in low-viscosity state and passive adaption is achieved since the MR fluid could easily flow around the delicate object with irregular shape. Once magnetic field is applied, the MR fluid filled pouch becomes rigid and the gripper can bear the load of object for manipulation and transportation. Majidi and Wood proposed a soft ribbon design with microchannels having MR fluid filled inside and the ribbon exhibited tunable elastic stiffness at low magnetic field [29]. This design was a promising alternative for stiffness modulation, although its robotic applications were yet to be discovered. Recently, ER fluids have also been applied in soft robotic applications. Figure 2d presents innovative soft fluidic actuator design using ER fluid as both control medium and actuation fluid [27,30]. ER valves are proposed for controlling the flow of ER fluid using its viscosity tuning property. In the upper panel of Fig. 2d, ER fluid flows through the spaces between the electrodes. When a high voltage is applied on the electrodes, the

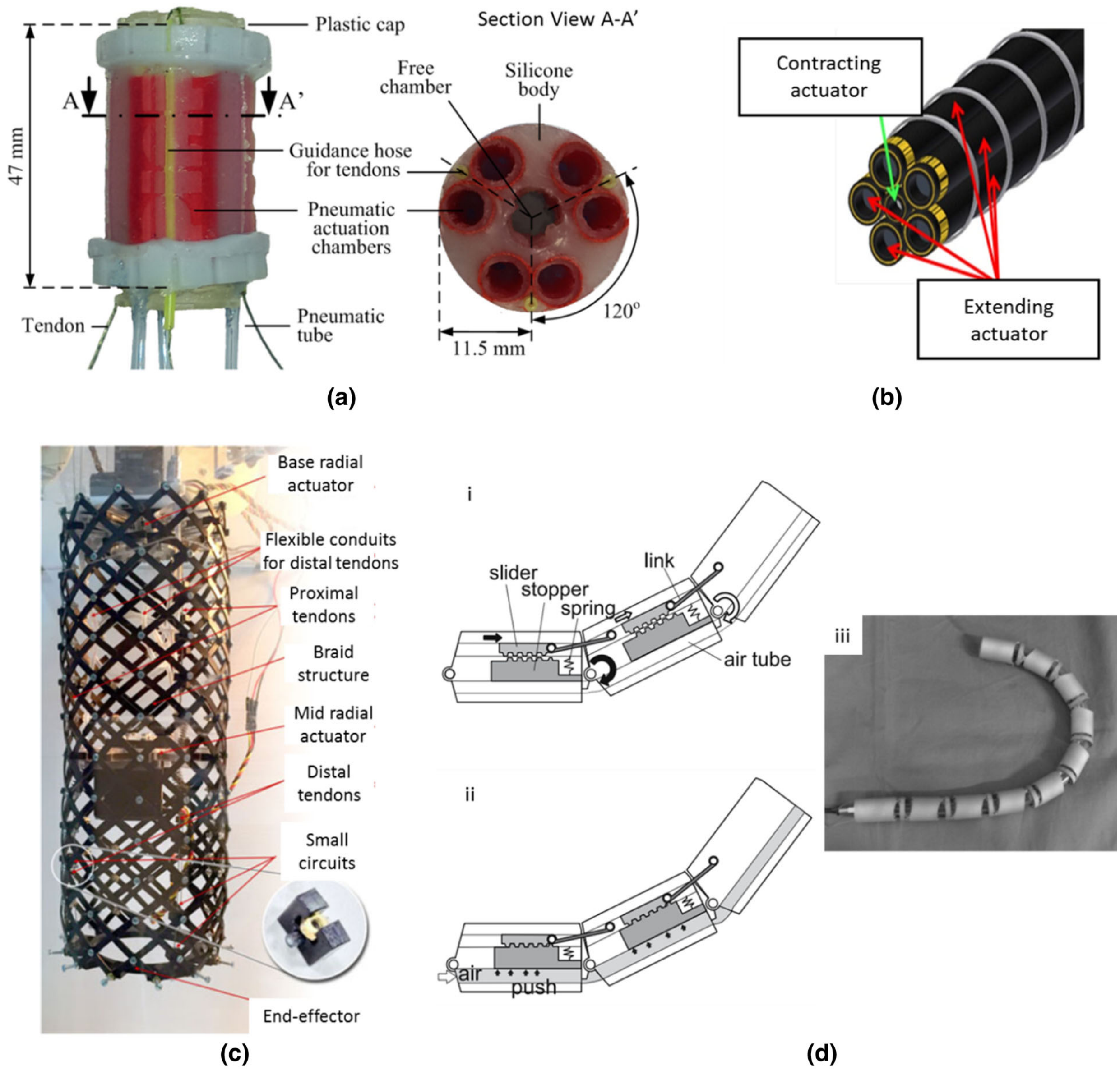

Fig. 4 Structure-based stiffness modulation methods. **a** A pneumatically actuated soft manipulator using tendons for stiffening [41]. **b** Configuration of combined contracting and expanding fluidic actuators to achieve variable stiffness [42]. **c** A continuum manipulator with actively tuned braid for variable stiffness [43]. **d** A flexible endoscopic manipulator with variable stiffness enabled by segment locking. *i* Each pair of the manipulator can move freely when air channel is empty. *ii* Shape of the sheath is locked when air channel is inflated and the stopper moves up to mesh with the slider. *iii* The manipulator prototype [46]

ER fluid transforms to high-viscosity gel state and the flow is blocked. When the voltage is released, the ER fluid returns to liquid state and the flow is restored. A flexible fluidic actuator system is fabricated for demonstration as shown in the lower panel of Fig. 2d. Thus, the stiffness of the flexible actuator can be modulated by electric field.

Jamming-based methods

Particle or granule jamming phenomenon has attracted many researchers' interest in the late 1990's [31] and is primarily studied by physics scientists [32]. Until 2010, Brown et al. [33] firstly introduced the jamming phenomenon into a universal soft gripper design that can grasp a variety of irregular objects without active feedback (Fig. 3a). Since then, many researchers have been investigating new soft robotic designs based on jamming principles.

Basic principle of particle jamming is shown in Fig. 3b [34]. At primary state, particles are loosely encapsulated inside a membrane sac with low stiffness since the particles can easily flow around. When air inside the membrane sac is evacuated, atmospheric pressure will apply on to the particle system, resulting in interparticle forces and high stiffness of the system. Wei et al. [35] integrated soft pneumatic actuator and particle jamming into a single finger design. The pneumatic actuator drives bending motion, while particle chamber provides a stiffness-changeable interface between the finger and the object being grasped. More recently, Robertson et al. [36] developed a vacuum-driven soft continuum robot utilizes particle jamming modules to realize active stiffness modulation. Their main novelty was that locomotion, jamming and suction were all enabled by vacuum power. Using the particle jamming principle, soft robotic locomotion is achieved by independently controlled jammed and unjammed cells in the robotic skin and the fluidic actuator inside the skin (Fig. 3c) [37]. When some cells are actively modulated from jammed to unjammed state, pressurized fluid would flow toward these unjammed cells, resulting in the robot's rolling motion. Even though particle jamming has attracted a lot of research interest for stiffness control, most previous robotic designs suffered from cumbersome vacuum pumps which limited their portability and usability. To solve this issue, Li et al. [38] proposed a novel soft actuator design based on passive particle jamming (Fig. 3d). In their design, the expansion of soft pneumatic actuator would squeeze the loosely packed particles during actuation and thus causing particles be passively jammed. As a result, the gripper was stiffened during grasping operations.

Apart from particle jamming, jamming phenomenon can also be generated with layered structure which is called layer jamming [39,40]. Kim et al. proposed a snake-like continuum manipulator for minimum invasive surgery (MIS) applications as shown in Fig. 3e. For layer jamming elements [Fig. 3e(i)], the overlapping surfaces between layers provide considerable frictional force when vacuum pressure is applied, thus increasing the stiffness of the manipulator. During applications, the manipulator can achieve both flexible motion (without vacuum) and large load bearing capability (with vacuum).

Structure-based methods

The three groups of stiffness modulation methods presented above are mainly based upon intrinsically adaptive materials whose elastic modulus/viscosity can be actively modulated under external stimulus. Aside from these methods, variable stiffness can also be achieved in soft robots mechanically by structural designs. Here we will illustrate several structure-based stiffness modulation designs reported previously.

Shiva et al. [41] designed a continuum silicon-based manipulator with variable stiffness realized by antagonistic actuation of pneumatic actuation and tendon (Fig. 4a). Their experimental results showed that the antagonistic actuation configuration increased the manipulator's load bearing capabilities. Except for stiffness modulation, the pneumatic and tendon-based actuation method endows the soft robot with the ability to control its pose. Another example of variable stiffness soft structures using antagonistic actuation is by combination of contracting and extending fluidic actuators as in Fig. 4b [42]. By driving the contracting and extending actuators concurrently, the combined mechanism can achieve stiffening effect. In research conducted by Hassan et al. [43], a variable stiffness continuum manipulator with active-braid inspired by muscular hydrostats is proposed and shown in Fig. 4c. In their design, the stiffness of the manipulator could be changed when the radial actuators and the longitudinal tendons were actuated antagonistically.

Segment locking is also a common approach for variable stiffness structures especially for flexible manipulators in medical applications such as MIS. By using a central or multiple tensioning cables to lock the segments, stiffness change can be achieved [44,45]. Tension in the cables leads to friction between segments and causes stiffness variation of the manipulator to adapt to different application scenarios. Except for controlling the tension of cables, segment locking of the manipulator could also be obtained via locking joints in the mechanism as shown in Fig. 4d [46]. The special geometry of the segment design guarantees that segments of the manipulator can be mechanically locked when air pressure is applied and thus high stiffness of the manipulator is achieved.

Summary

To summarize, glass/phase transition-based methods are usually thermal-induced which requires heating elements for de-stiffening and is not energy efficient. For these methods, cooling is much slower when no sophisticated cooling device is installed. Among glass/phase transition-based methods, SMP and LMPA can achieve the largest stiffness variation ratio (8600 times in modulus for LMPA [47], 300 times for SMP [48]). Viscosity-based methods include MRF, ERF and their composites which can be activated in milliseconds. However, affiliated devices to generate magnetic/electric field are essential and for ERF the high driving voltage 1–5 kV [30] is not preferred in soft robotic applications especially when interacting with human beings. Pressure-induced method can achieve fast stiffness variation, and the variation ratio is considerable (up to 50 times for particle jamming [49]). One limitation is that vacuum pump (which is usually large and noisy) is needed to generate the jamming effect. For passive particle jamming without vacuum pump, the stiffness change is coupled with actuation and actuator deflection. The stiffness variation ratio is small (up to 6 times [38]). Structure-based methods include designs with antagonistically arranged actuation and segment locking. Compared to other three groups of variable stiffness methods, structure-based method usually has sophisticated mechanism designs which may complicate the fabrication and control of these

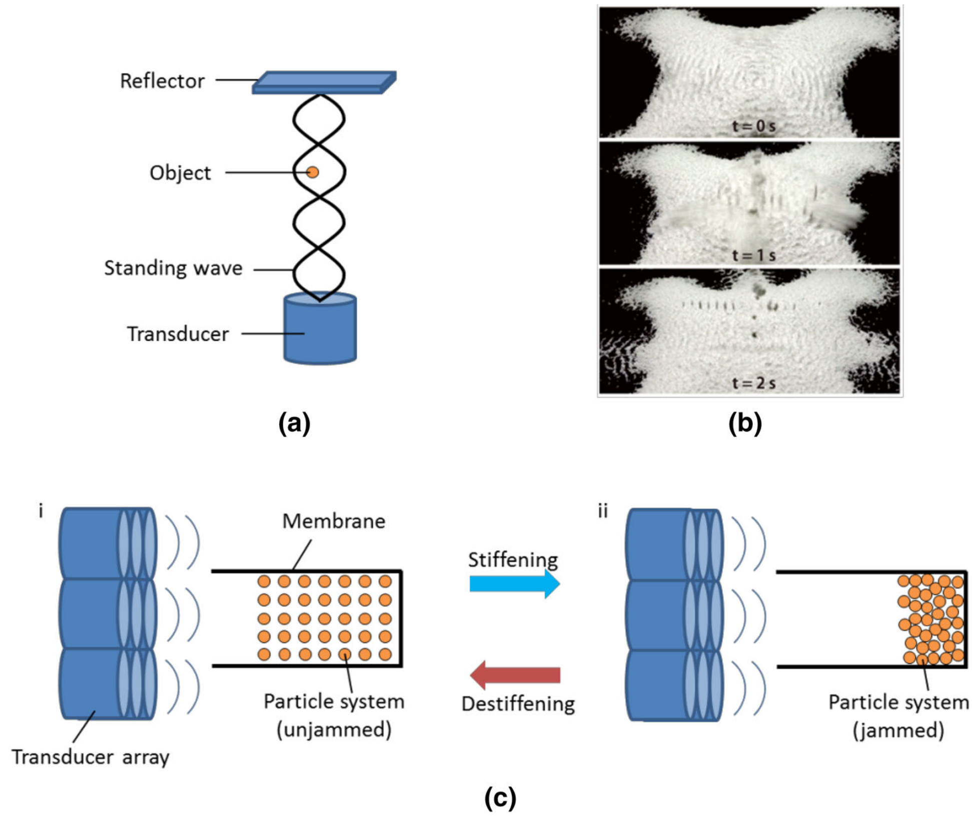

Fig. 5 Principle of acoustic levitation/manipulation-based stiffness tuning. **a** Diagram showing the principle of acoustic levitation. 1D acoustic levitation with standing wave generated by a transducer and a reflector [56]. **b** 3D manipulation of particles with four transducer arrays [58]. **c** Proposal for acoustic-based variable stiffness method by altering the state of a particle system wrapped in membrane with acoustic manipulation. *i* The particles are loosely arranged, and the stiffness of the particle system is low. *ii* The particles are jammed by altering the distribution of acoustic field

mechanisms. By summarizing the existing methods, there is no method that obviously outweighs other methods in realizing stiffness variation for soft robot design and development. With rapid progress in soft robotic research, it is believed that more new and promising methods for stiffness modulation will emerge in the near future. The following presents a potential method for stiffness modulation in soft robots that has been investigated by the authors.

A potential method for stiffness modulation

Except for the four categories of stiffness modulation methods presented in second section, here we propose acoustic-based methods as the potential fifth category. Hopefully, this new method would confer soft roboticists with more choices for stiffness modulation.

Wireless actuation is a promising direction in robotic research since the robots would no longer suffer from onboard batteries. As a result, applications in enclosed places (e.g., human body) would be possible [50–52]. Wireless actuation can be achieved by electromagnetic power transmission which has been applied in robotic folding [52]. Apart from electromagnetic power transmission, acoustic energy is another potential candidate for wireless power transmission.

Acoustic levitation-/manipulation-based stiffness tuning

Wireless/noncontact manipulation powered by acoustic energy has already been applied in cell manipulation [53], containerless transportation [54] and lab-on-a-chip scenarios [55]. The principle of acoustic levitation/manipulation is that acoustic traps are formed by standing waves to provide suspending force against gravity and thus objects are trapped and levitated (Fig. 5a) [56]. Based upon the basic principle, researchers have realized 2D and 3D manipulation of levitated objects with transducer arrays [54,57,58]. Snapshots of particles' levitation and manipulation with four transducer arrays are shown in Fig. 5b.

Inspired by acoustic levitation/manipulation, we are investigating potential acoustics-based noncontact actuation and stiffening of soft robots. Since particles can be manipulated by acoustic waves and different particle arrangements can create jamming and unjamming effect, a reasonable assumption is to use acoustic method to change the arrangement of particles and thus changing the stiffness of a particle pack. Diagram of the proposed method is shown in Fig. 5c. At primary state (unjammed state), the particles do not have contact or are loosely in contact with each other and the whole particle pack exhibits low stiffness. By altering the distribution of acoustic field with transducer arrays, the particles rearrange to generate jamming effect, the stiffness of the particle sys-

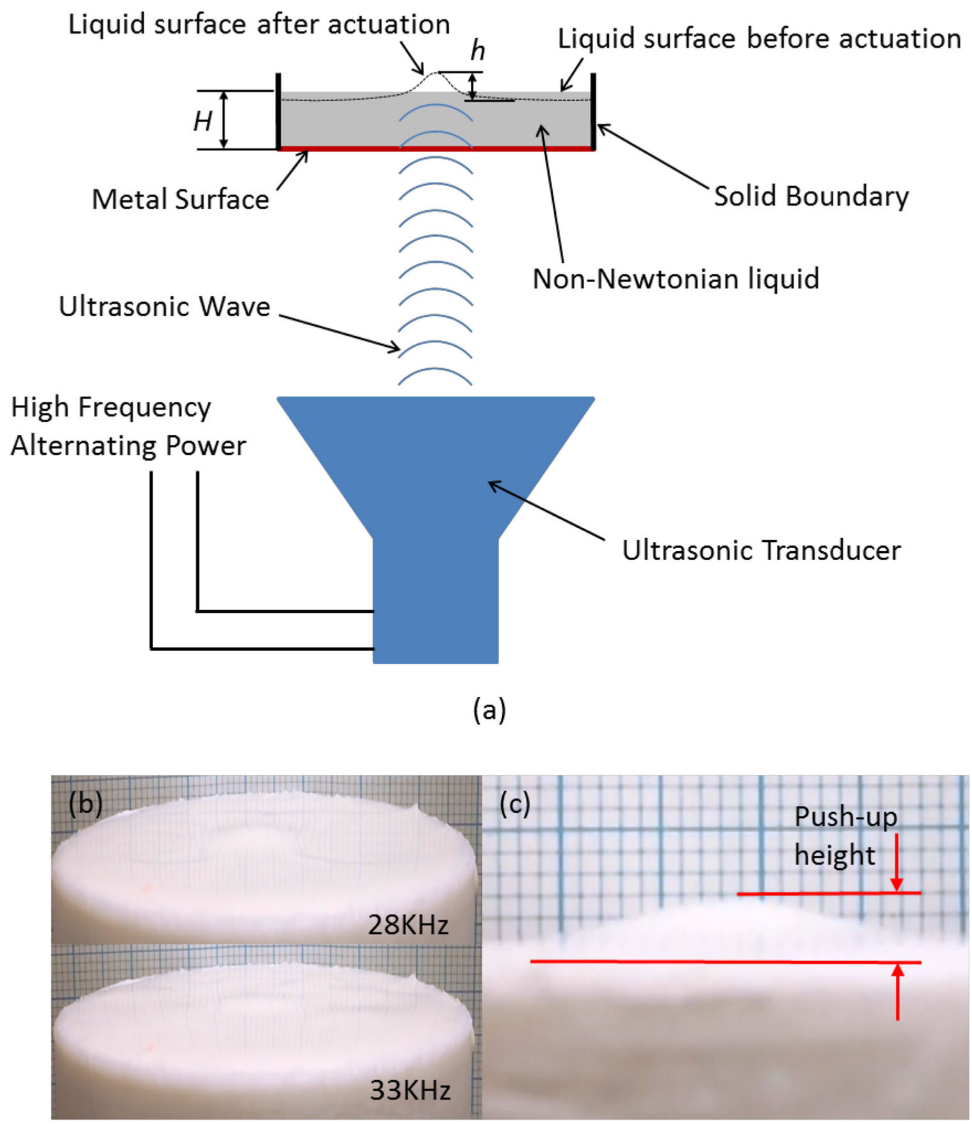

Fig. 6 Actuating non-Newtonian liquids using an ultrasonic transducer. **a** Experimental setup. **b** The surface geometry when actuated by ultrasound with different frequency. **c** Side view of the liquid surface geometry and the definition of push-up height

tem is changed. The transfer between unjammed and jammed states is reversible by controlling the acoustic field.

Currently, the particles used in 3D acoustic manipulation are mostly made of polystyrene with low weight. To realize variable stiffness, particle materials and membrane materials should be carefully chosen and the configuration of transducer arrays as well as reflectors should be further investigated. Another challenge is how to increase the power density of acoustic manipulation in order to make this technique suitable for soft robotic applications.

Acoustics for liquids actuation and variable stiffness

In reviewing ultrasonic levitation, it is found that liquid drops can also be levitated in ultrasonic field [59]. This phenomenon inspired us to investigate the possibility of acoustic power-driven soft robotic design and development.

Investigation of acoustic actuation of liquids

For ultrasound generation, a piece of piezoelectric material is normally used [60]. When the piezoelectric material is stimulated by high-frequency alternating current, the material will show periodically measurable deformations. With this feature, the piezoelectric materials are used to design and fabricate microultrasonic actuators and pumps. However, no previous articles have reported direct actuation of a large amount of liquid. In our investigation, three types of liquids are chosen and tested. They are pure water, mixture of water and oil and non-Newtonian liquid formed by mixing corn flour powder with water. The ultrasonic transducer used in this experiment is Sonic Levitation Machine (from *Soniclevitation.com*).

The experiment setup is shown in Fig. 6a. In this experiment, we put the liquids container directly on top of the

Table 2 Main parameters of the liquid actuation experiment

Parameters	Values
Ultrasonic transducer frequency	28 kHz
Ultrasonic transducer power	50–70 W
Non-Newtonian liquid volume	2.64 cm^3
Volume ratio (corn flour powder /water)	1.5
Liquid height H	1 mm
Push-up height h	2.7 mm

ultrasonic generator surface. Main parameters regarding to the liquids actuation experiment are listed in Table 2.

Preliminary experimental results

The tests to actuate water or the mixture of water and oil generated no visible effects. The potential reason may be that the water and mixture of water/oil are more like a transmitting medium of ultrasound, similar to air but with different density. When ultrasound reaches the liquid, it can pass through the liquid with limited energy loss. And the basic molecules of water and oil are too small to show visible effect even when they are stimulated by ultrasound.

However, some interesting findings were recorded and reported here when the non-Newtonian liquid (a water and corn flower solution) was tested as in Fig. 6b, c. By changing frequency of the ultrasound, the liquid shows large visible deformation which might be tapped for soft robot actuation. Some findings were summarized below.

First, the ultrasonic power did push up the liquid and generate a 3D dome like shape. Second, the frequency of the ultrasound transducer has great impact on the size of the dome like shape. By varying the frequency, the liquid surface geometry would show corresponding change as shown in Fig. 6b. To quantify the effect of ultrasound, the push-up height is indicated in Fig. 6c. Third, the maximum height of the push-up in the liquid appeared when the ultrasound's frequency equals to transducer's natural frequency. The natural frequency of the ultrasonic transducer we used is 28 kHz, and from Fig. 6c, the maximum push-up height can reach 2.7 mm. Fourth, by changing the ratio of corn flour and water of the non-Newtonian liquid, the visual effect will be different. When the volume ratio of corn flour powder and water is 1.5, the push-up effect is the best in our experiments.

The phenomenon that non-Newtonian liquid shows visible deformation could possibly be utilized in the field of soft robot's actuation. Principle of the push-up phenomenon may be explained by acoustic streaming [61], which is an acoustic generated fluid flow. It is the dissipation of acoustic energy that leads to gradients in momentum flux and thus generating acoustic streaming motions [62]. For water or the mixture of water/oil, a large portion of acoustic energy from the ultrasound transducer might pass through the liquid as explained above. Therefore, no obvious push-up is observed. For non-Newtonian liquid, the particle suspensions (corn flour powder in this test) may trap acoustic energy within the liquid and this dissipated acoustic energy is expressed in the form of the non-Newtonian liquid's push-up deformation.

Potential for variable stiffness

The above experiments have shown that a non-Newtonian liquid will experience deformation when actuated by ultrasonic energy. If an elastic membrane/film is used to restrict the push-up deformation of the non-Newtonian liquid, then pressure will be generated within the liquid, resulting in an increase in the structure's stiffness. Currently, we are still working on practical designs incorporating ultrasonic transducers for soft robotic stiffness modulation.

Conclusions

To effectively interact with the environment, the capability of stiffness modulation is crucial for soft robots. This paper has reviewed existing stiffness modulation principles and methods that have been used for soft robotic design and development. These methods include glass/phase transition-based methods, viscosity-based methods, jamming methods and structure-based methods. It is found that all stiffness modulation methods have their own problems, limiting their widespread applications. Thus, there is still ongoing research for more innovative stiffness modulation principles and methods. This paper has argued that acoustic principle has the potential for soft robot actuation and stiffening. Based on acoustic principle, two methods for stiffness modulation have been investigated and experimentally tested. So far, visible results have been obtained, based on which, the authors have identified the potential roles of acoustic energy in soft robot design and development. It is expected that this review could inspire more researchers to investigate novel stiffness modulation principles and methods for soft robotic applications.

Author contributions YY, YTL and YHC designed the overall study. YY and YHC wrote the manuscript. YTL performed the experiment of acoustic liquids actuation. YY and YTL analyzed the data. YHC supervised the study. All authors commented on the paper.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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