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REGULAR PAPER

# A novel approach to enhancing smart stiffness of soft robotic gripper fingers for wider grasping capability

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## Abstract

This paper presents a proposed design of soft gripper fingers with adjustable stiffness that could be employed in the applications requiring adaptable and stable grasping. The main idea is to combine the under-actuated cable driven mechanism of a soft gripper finger with particle and layer jamming mechanisms to create a new grasping function with variable stiffness for different manipulation requirements. The movement of the soft gripper finger is produced by a cable-driven mechanism. However, particle and layer jamming chambers were embodied as a variable stiffness mechanism for the variable stiffness function. A single soft gripper finger module was developed and tested with particle and layer jamming chamber attached to it. The stiffness and response time of the soft gripper finger were measured in three distinct configurations: single finger module, particle jamming chamber attached to the finger, and layer jamming chamber attached to the finger. The comparison reveals that combining a soft finger with particle jamming increased performance by 20% compared to using the soft finger alone, while combining it with layer jamming led to an 80% increase. Additionally, layer jamming combined with a soft finger showed a 28% increase compared to particle jamming combined with a soft finger. Furthermore, simulation of the soft finger was conducted to estimate the deflection of the soft gripper finger under various applied forces. Moreover, proposed closed loop smart stiffness mechanism for the soft gripper was modeled and simulated by evaluating both soft and hard objects and simulation results were obtained for different cases. The findings indicated that the stiffness of the soft gripper finger can be adjusted for different grasping requirements.

**Keywords** Soft gripper: variable stiffness · Combined actuation technology · Adaptive grasping

## 1 Introduction

Soft robotics is a rapidly evolving field with significant implications for various applications, the field of soft robotics presents intriguing opportunities for researchers to develop systems that can adapt to and function in various environments. Furthermore, it bridges the gap between humans and devices or machines. An example of this is the development of soft wearable robots (SOFT Robot WALKS 2011; Ansari et al. 2015; Abu Bakar et al. 2007). The primary distinction between soft robotics and traditional hard robotics lies in their respective Young's modulus. Hard robotics typically have a high Young's modulus, around $10^{12}$ Pa. In contrast, soft robotics have a significantly lower Young's modulus, up to $10^{5}$ Pa. This difference is crucial as it allows soft robotics to exhibit adaptability and flexibility when encountering obstacles (Rus and Tolley 2015).

Conventional rigid robotic gripper systems with end effectors are used in automotive industry, food industry and medical applications to pick and place different components (Cianchetti et al. 2018). Conventional rigid robotic gripper systems are durable and can exert greater forces compared to the soft grippers. However, high level of dexterity and sensitivity, such as handling food, interacting with biological tissues in medical procedures, or manipulating fragile objects

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can be achieved by using soft grippers. In some scenarios the need of soft grippers is essential to extend the range of objects to be grasped. Because the soft grippers are adaptable that can grasp delicate and irregular objects compared to the conventional rigid grippers. Therefore, Soft material and actuation can be combined to develop soft gripper devices that could safely interact with the surrounding and perform tasks such as grasping and handling different components.

Some examples of soft grippers that are based on different types of soft materials and actuation methods are reported in the literature (Shintake et al. 2018). Exploiting soft material in the design of soft grippers brings safer interaction in manipulating soft, fragile, brittle objects typically found in food industry in general such as cake manufacturing. This exploitation also generates benefits with human interaction in human -robot collaborate working in grasping in a changing environment. Moreover, soft grippers are aimed to perform tasks such as grasping and handing using soft actuators (Li et al. 2019; El-Sayed et al. 2013). Therefore, grippers are expected to have capacities that are based on the actuation mechanism, material properties, and morphology of their bodies (Shintake et al. 2018). Current soft robots or grippers, such as the octopus can manipulate objects. Another type of soft gripper based on electrostatic actuation. The gripper could grasp objects such an egg and a sheet of paper, but high voltage is needed to drive the mechanism of the gripper. A compliant and dexterous hand was presented in which the soft hand is actuated by pneumatic actuation system (Deimel and Brock 2015a, b; Wang and Hirai 2018). The hand could lift objects nearly three times its own weight. A soft gripper with adjustable stiffness and variable working length for handling food products, particularly little pieces of food was presented (Wang and Hirai 2018). Experiment results showed that by inflating the cover chamber with varying air pressures, the bending stiffness and working length can be changed. The soft hand showed compliance during several grasping scenarios.

The end effectors should be able to interact and grasp components of different shape and size (Lien and Caldwell 2012). Also, those components must be and securely grasped and handled without damaging them. The handling of irregular objects introduces demands on gripper in terms of warping different shaped objects, and payload capability through grasping with stiffness (Petković and Pavlović 2012; Bogue 2016). The flexibility of the soft gripper can be obtained by selecting the main structure, such as silicone rubber, which has flexibility characteristics (Lei et al. 2022). However, the compliance of the soft gripper could be achieved by varying the stiffness of the gripper using variable stiffness mechanism (Wall et al. 2015; Nguyen et al. 2019; Jujjavarapu et al. 2019). Although, exploiting the softness of the material is beneficial to perform soft machine-target contact (Manti et al. 2015a). Softness of the material limits the amount of force that exerts to the objects to be handled. Because of this, a tunable stiffness is needed to vary the stiffness of the gripper to adapt with variety of objects that are requiring certain amount of rigidity during the interaction (Cianchetti et al. 2013).

On the other hand, controlling the stiffness of the gripper body to be adapt with different types of objects has to be taken into account (Smith 1989). In other words, transition between passive state and active state is a great challenge (Wei et al. 2016; Wang et al. 2019). The passive state concept can be obtained through the use of particle jamming, which does not require any vacuum power or other control techniques. So it is simple to create soft grippers with a wide range of stiffness variation driven by a small actuation pressure using the concept of passive particle jamming (Li et al. 2017; Amend et al. 2012). On the other hand, the active state concept can be achieved by using a shape-memory alloy (SMA) (Liu et al. 2020; Tadesse et al. 2011; Meng et al. 2020). Additionally, electroactive polymers can be employed to generate active stiffness states for soft robotic grippers. which responds to electrical stimulation by changing its form or size (Cheong et al. 2018).

There are approaches reported in literature that could tune the stiffness of the soft gripper. Firstly, stiffness variation based on tuning of material properties using intrinsic material effects. secondly, tuning the stiffness of an entire structure is to change its geometry (Raatz et al. 2015; Fitzgerald et al. 2020). Particle jamming represents a type of stiffness alteration. This technique is employed in the creation of a soft actuator, which is filled with various particles (Chen et al. 2024). The primary achievement of this work is the creation of a soft actuator that incorporates both rigid and deformable particles. As a result, the soft actuator can undergo significant bending deformation due to membrane contraction or particle expansion. The use of numerical simulation was instrumental in confirming that the soft actuator and deformable chamber structure can support extensive deformation behavior. The particle jamming effect was utilized to achieve variations in stiffness. Another recent study introduced a soft actuator for hand rehabilitation (Pan et al. 2022). This actuator can adjust its stiffness based on the addition of a stiffener to its main structure, a function inspired by the properties of bamboo fiber (Lv et al. 2024). In this soft actuator, both the output force and bending torques were experimentally quantified. Additionally, the results from the simulations were found to align with the experimental data. The research highlighted a rapid response, which is beneficial for closed-loop control. The stiffness of the gripper could be tuned, but there is some limitation in the range of stiffness due to inherent properties of the soft material. There is jamming based systems that can be used as strategies to change the stiffness of the gripper (Manti et al. 2016). For example, granular gamming that has the capability to tune the material from the liquid state to the solid state and vice versa. These jamming-based systems seem to be simple to be used and combined with robotic systems. So, jamming mechanisms have laid the groundwork for pioneering a new paradigm in soft robotics.

Layer jamming principle is one sort of stiffness variation mechanism that is based on the tuning of material properties (Narang et al. 2018). A pneumatic actuator is used to drive the jamming layer. The driving layer might flex due to air pressure, and the jamming layer can vary in stiffness. The bending angle of the driving layer is dependent on the pressure differential when actuated by air pressure (Fitzgerald et al. 2020). A high- force soft pneumatic actuator was presented that is consisted of that consists of a spring, an eccentric silicone cylinder, and a limiting fiber (Cheng et al. 2022). The tip force and response time of the developed actuator were experimentally characterized. The results showed the large tip force and fast response capability of the actuator. The soft pneumatic actuator that was developed has been utilized to assemble a three-fingered soft gripper. This soft gripper has the capability to successfully grasp objects of varying sizes and shapes, and can handle objects weighing up to 1.25 kg. A soft robotic gripper based on layer jamming was presented to provide high adaptability and payload (Zeng and Su 2023). This research shows that the method of layer jamming, which actively adjusts stiffness, in conjunction with a 3D printed soft finger, effectively enhances the payload capacity of soft grippers.

Also, layer jamming principle has the advantages of acceptable range of stiffness variation (Wall et al. 2015; El-Sayed et al. 2014). Thus, a desirable option to be explored for a potential adoption within an overall cable drive mechanism to design soft robotic gripper. A bioinspired soft manipulator was introduced based on granular jamming based mechanism (Ranzani et al. 2015). The soft manipulator is used for minimally invasive surgery (MIS) and it is composed of soft materials and it has been designed to provide similar motion capabilities as the octopus's arm (Sadati 2015). different research work was presented to show the stiffening capabilities of soft actuators based on jamming (Wall et al. 2015). The stiffening mechanism based on granular and layer jamming as two possible methods to achieve stiffening with PneuFlex actuators (Deimel and Brock 2015c). On the other hand, tuning the stiffness of an entire structure was found in variable stiffness mechanism using wire spring (Hayashibara 2008). A robotic gripper design with variable stiffness was proposed and fabricated a modified additive manufacturing (Yang et al. 2016). The robotic finger's movement is powered by a pneumatic soft actuator. The creation of this innovative finger design is facilitated by an adapted 3D printing technique. A theoretical model has been established to illustrate the correlation between the air pressure in the soft actuator and the deflection angle of the finger. A robotic gripper, designed to be compliant, has been unveiled, featuring three fingers with adjustable stiffness. The fingers' shape-shifting ability is facilitated by a cable-driven mechanism, while the alteration in stiffness is made possible through a process known as layer jamming (Gao et al. 2020). Another jamming techniques that is based on filament jamming was presented to produce variable stiffness structure (Hu et al. 2021). The jamming of filament under a vacuum pressure provide softness and shape adaption that can meet different applications. The study indicates that the filament jamming structure showcases a rapid response and adaptable impedance performance. Our research highlights the multifaceted capabilities of jamming technology, such as shape adaptability, shape retention, stiffness consistency, and flexibility.

This paper aims to address these challenges by exploring the design and operation of a soft robotic gripper finger driven by cable technology. Specifically, it investigates how the attachment or detachment of jamming chambers can facilitate easy adjustment of the gripper's stiffness. The study also examines the effectiveness of these jamming chambers in modifying gripper finger stiffness and assesses the gripping force on objects of varying hardness through a closed-loop simulation model. The proposed closed-loop control scenario aims to offer potential enhancements for future control algorithms.

This paper attempts to provide response to the following research questions:

1. How does the design and operation of a soft robotic gripper finger, driven by cable technology, enable it to adapt to the shape of an object, and how does the attachment or detachment of jamming chambers allow for easy adjustment of the gripper's stiffness?
2. What is the role and effectiveness of the jamming chambers in changing the stiffness of the gripper fingers when required?
3. How does the closed-loop simulation of the soft gripper model perform when assessing the gripping force on objects of varying hardness, and what potential enhancements for the control algorithms does the proposed closed-loop control scenario offer for future developments?

## 2 Materials and methods

### 2.1 Basic requirements and specifications of the proposed design concept of the soft gripper finger

In this section the design requirements and specifications of the soft gripper are presented in order to meet certain requirements in the area of food industry as an example. As a proof of concept in formulating soft gripper design specifications, a set of requirements have been listed in Fig. 1. In specific, two main aspects are highlighted to fulfil the requirements of developing the soft gripper. Firstly, technology used in the design of soft gripper. Secondly, soft material that is used in the design of gripper finger and both particle and layer jamming chamber.

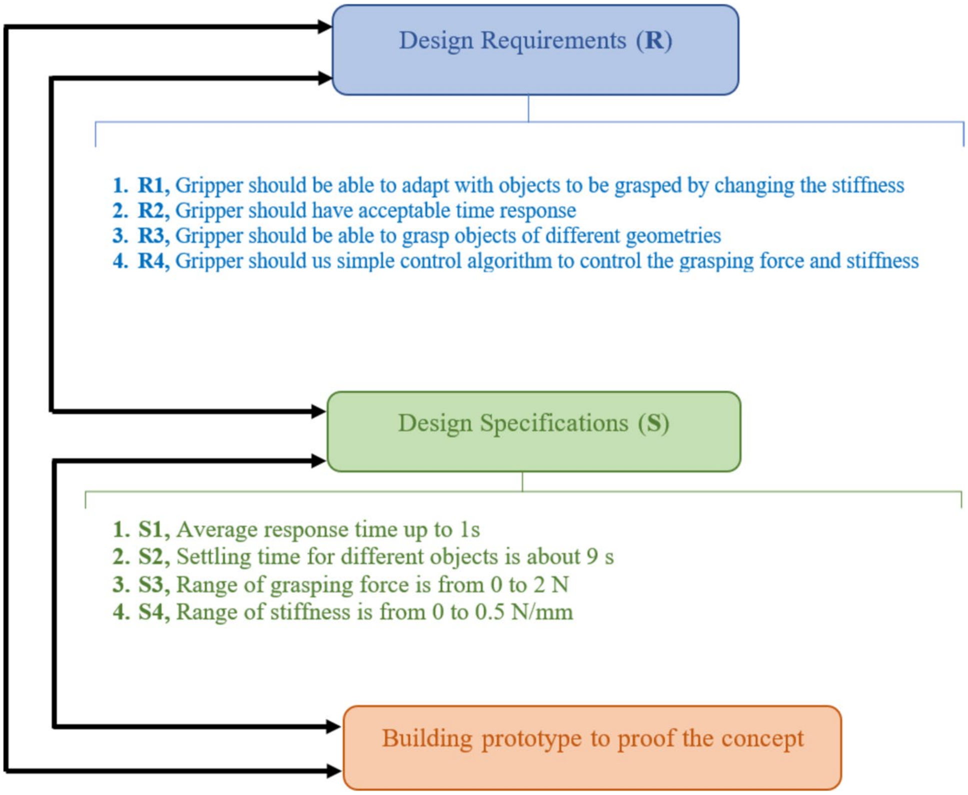
In order to select the technology of actuation that could meet the design requirements and specifications. It is found that the actuation of the soft finger can be achieved using single motor and actuation cable (Hussain et al. 2021).

In under-actuation mechanism, number of degrees of freedom (DOF) is greater than number of actuators. Under-actuation mechanism has low inertia, light weight, and low time response (In et al. 2011). The device is adaptable to various object shapes. In addition, Under-actuation mechanism tends to enhance the compactness of the gripper as well as to imitate the human muscular principles (Luo 2013). Therefore, Under-actuation mechanism could be an appropriate approach to meet the design requirements of the gripper.

Selection of soft materials can provide deformation during interaction between the gripper and the environment (different objects) [62]. Thus, the body of the gripper can be deformed due to the flexibility of the soft material used and as a result it can adapt with the shape of the object. On the other hand, exploiting soft material with variable stiffness can simplify the overall control scheme of the gripper system. For example, silicone elastomer that has low modulus of elasticity can be used to provide softness to the gripper fingers. Another approach to control the stiffness of the material is to embed it with stiffer materials such as wax [63] or metal [64].

## 2.2 Proposed configuration of the soft gripper finger: single finger module, particle and layer jamming chambers attached to the soft gripper

The design of the finger was inspired from the human finger itself. The finger mimics the human finger in shape, three phalanges, and dimensions (Manti et al. 2015a; Hassan et al. 2015). The material of the finger is fabricated from soft silicone materials Dragon Skin 30 (Smooth-On, Inc.), with an elastic modulus of 1 MPa (Fig. 2e) (Hassan et al. 2015). The finger is actuated by using single servo motor and actuation cables, as the actuation cables mechanism has previously been used in various approaches (Manti et al. 2015a, b; Dong et al. 2018). The actuation cable is a single wire loop which passes through tubes that are embedded inside the soft finger and U-tubes placed inside the distal phalanx (Manti et al. 2015c). A pulley is attached to the shaft of the servo motor, as the servo motor is actuated the overall length of the wire that is wound on the pulley, hence the length of the wire is reduced and that is allowing the finger to bend.



1. **R1,** Gripper should be able to adapt with objects to be grasped by changing the stiffness
2. **R2,** Gripper should have acceptable time response
3. **R3,** Gripper should be able to grasp objects of different geometries
4. **R4,** Gripper should us simple control algorithm to control the grasping force and stiffness

1. **S1,** Average response time up to 1s
2. **S2,** Settling time for different objects is about 9 s
3. **S3,** Range of grasping force is from 0 to 2 N
4. **S4,** Range of stiffness is from 0 to 0.5 N/mm

**Fig. 1** Overall system requirements and specifications

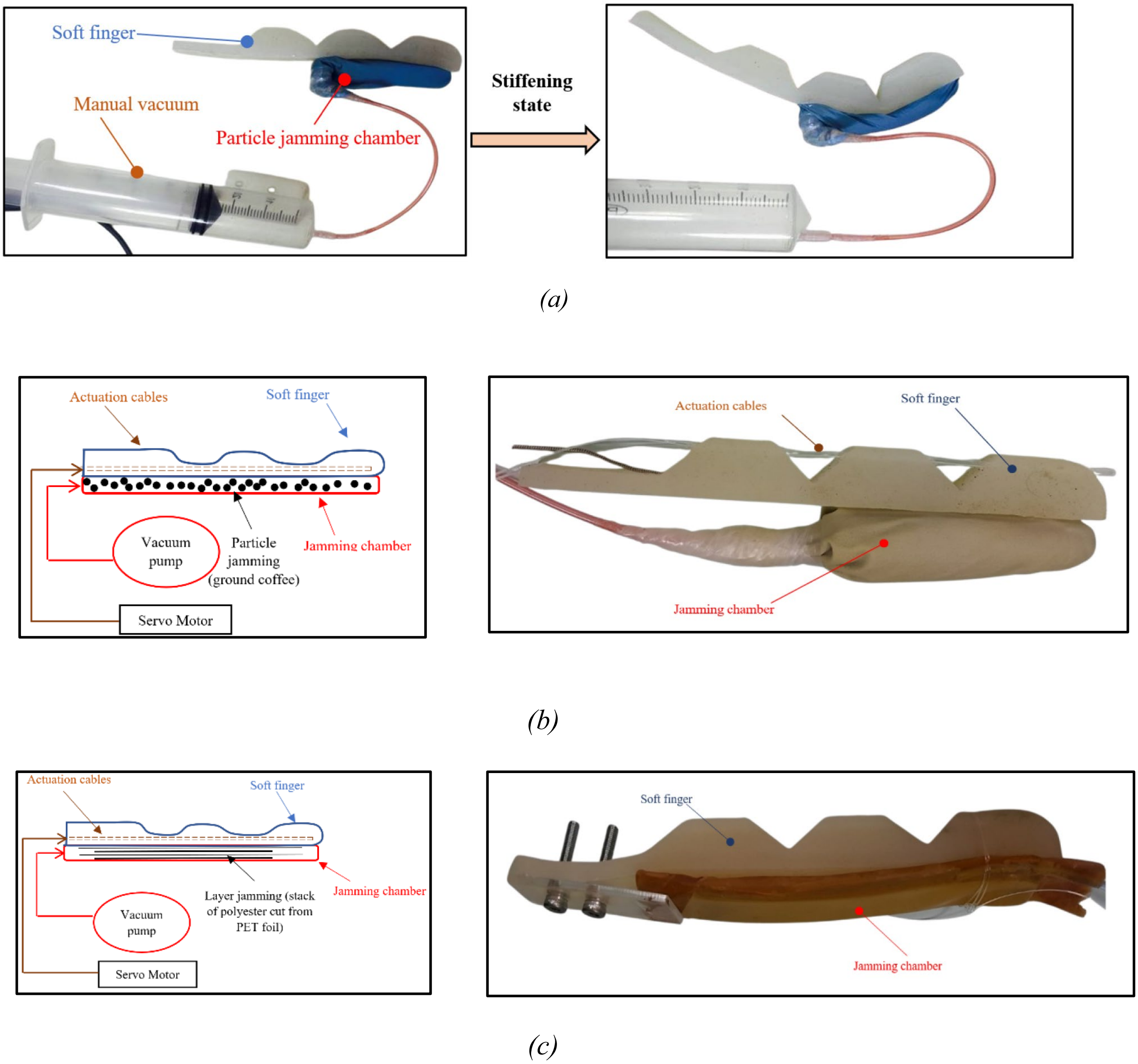


**Fig. 2** **a** Unjammed state of the soft finger on the left hand side and jammed state of the soft finger on the right hand side, **b** actual combination of particle jamming chamber with the soft finger (schematic on the left and actual representation on the right), **c** actual combination of the layer jamming chamber with the soft finger (schematic on the left and actual representation on the right)

Stiffness variation mechanisms are found in some previous research work that are based on either tuning of material properties using intrinsic material effects or tuning the stiffness of an entire structure by changing its geometry. In the present work, the idea is to combine the under-actuation cable driven mechanism that provide the movement of the soft gripper finger with particle or layer jamming. The movement of the fingers is provided by the motor and cable transmission. The particle or layer jamming chamber, on the other hand, is responsible for the variations in stiffness of the fingers. For example, grasping objects that require stiffer fingers can be accomplished by activating the layer jamming chamber. To achieve certain requirements, particle and layer jamming both need to be enabled in some circumstances. However, in order to control the stiffness in different scenarios, particle or layer jamming chamber may be attached to the soft gripper finger. In specific, the current research investigates the combination of under-actuation cable driven mechanism with particle (Granular) and layer jamming.

The particle jamming chamber in the current work was made using ground coffee as it is easy to acquire, completely harmless, and offers good weight-to-strength ratio

(Wall et al. 2015; Wei et al. 2016; Hou et al. 2019).The stiffening coffee chamber has a cylindrical shape filled with ground coffee. A six grams of ground coffee within a volume of 15 cm$^3$ compartment. The coffee chamber filled with ground coffee is shown in Fig. 2h (on the bottom). In the current research also a layer jamming was adopted as it is potentially uses the available volume in an efficient manner (Wall et al. 2015). The structure of the layer jamming consists of two interleaved stacks of sheets that are fixed at the end of the gripper finger. The sheets are made from 100 µm a thermoplastic material (PET) foil and are separated from each other by 800 µm within a stack. Each stack consists of four interleaved layers, resulting in 8 layers total (Fig. 2h on the top).

In order to vary the stiffness of the soft gripper finger, particle or layer jamming methods can be used. The soft finger can be changed from unjammed state to jammed state by attaching a particle jamming chamber as shown in Fig. 2i. Jamming is induced by increasing density in the flexible membrane due to the applied vacuum. A syringe has been used to show the behavior of the soft finger structure from an unjammed state to a jammed state. Two approaches of particle and layer jamming have been experimentally applied to check the combination of those two capabilities with cables actuation mechanism. Those two approaches can be exploited in the future development of soft gripper fingers. The two approaches will be discussed in the following sections in terms of: (1) Cables actuation combined with particles jamming, (2) Cables actuation combined with layers jamming.

In particle jamming, individual particles get compressed together, locking each other in place. Hence, this method is called particle jamming or other similar particles. Coffee powder can be used as granular material and latex as containing membrane. Jamming is induced by increasing density in the flexible membrane due to the applied vacuum. By controlling the vacuum level, the stiffness can be to a level suitable for a requirement (Fig. 2a, f). Layer jamming replaces granular material with sheets that stiffen when pressed against each other [70]. Forces between individual sheets are spread over a large area of contact, greatly reducing the pressure required to maintain stiction. The structure of the layer jamming consists of two interleaved stacks of sheets that are fixed at the end of the gripper finger. The sheets are made from 100 µm PET foil and are separated from each other by 800 µm within a stack. Each stack consists of four interleaved layers, resulting in 8 layers total Fig. 2b, g show the soft finger with a layer jamming chamber are attached with a cable mechanism and the actual combination respectively.

## 3 Experimental characterization setup

In this section, the experimental setup of the soft finger's performance in terms of stiffness at different types of jamming methods will be presented. In order to characterize the performance of the soft gripper finger, three cases of soft finger mechanism will be considered in order to test the capability of resisting deformation of the soft finger in response to external forces in each case. Also, the experiments considered the response time, which indicates the soft finger's speed of reaction. The procedure involved measuring the response time for three scenarios: the single module soft finger, the single module soft finger with particle jamming, and the one with layer jamming chambers attached. Detailed findings are provided in the results section.

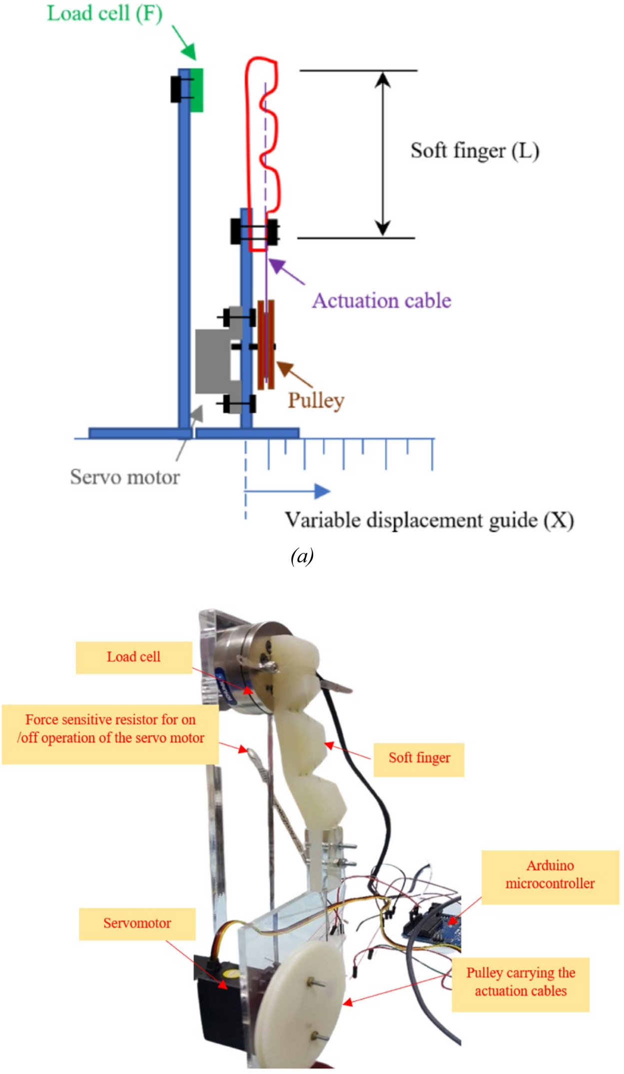
### 3.1 Tests of the single soft finger module

#### 3.1.1 Part 1: test for under actuation soft gripper finger

The soft finger is fixed in such configuration as shown in Fig. 3. By considering the unidirectional actuation nature of the proposed soft finger, loading can be classified into (1) External force F with corresponding displacement X along the bending plane (axial) as shown in the schematic diagram in Fig. 3a. The force developed by the soft finger module was measured by positioning an ATI Mini45 load cell. In the test setup as shown in Fig. 3b, the finger is actuated by a servo motor that is attached to pulley system which is pulling the actuation cables. A pulling cord connects the tip of the testing finger with the face of the load cell. Arduino Uno and FSR (force sensitive resistor) have been used to operate the servo motor in order to provide the movement to the soft finger. The single module finger was tested while the under actuation is activated, and the force was measured using the load cell. The experimental procedure started by activation of the servo motor via the FSR. The single module finger began to be bended to the full range, simultaneously a strip is attached into the finger along with the load cell in order to measure the tension force at this case.

### 3.2 Part 2: test of under actuation mechanism combined with particle jamming for soft gripper finger

In Fig. 4, activation of particle jamming chamber that is attached to the soft gripper finger was performed. It was assumed that the cable ties are affixed at the ends of the jamming chamber on both sides. Consequently, it is considered that the active segment of the jamming chamber to be the area between these attachment points. The test was



(a)

(b)

**Fig. 3** Measurement setup for the soft gripper finger, **a** schematic diagram of the setup and **b** experimental setup

conducted in three steps; firstly, while the finger in a vertical case and the particle jamming chamber was active. Secondly, the particle jamming was an activated and then the soft finger has been bended by using the actuation cables. Thirdly, the particle jamming was activated while the soft finger in the bending state.

#### 3.2.1 Part 3: test of under actuation mechanism combined with layer jamming for soft gripper finger

Similar test procedure has been performed to test under actuation mechanism combined with layer jamming for soft finger (Fig. 5). The layer jamming chamber has been activated while the soft finger in bending state in order to check the stiffness of the whole structure at the combined state of the under actuation with the layer jamming.

### 3.3 Configuration of the two fingers gripper

The two fingers gripper combined with particle chamber and layer jamming can be shown in Figs. 6 and 7 respectively. The actuator (servomotor) provides motion to the soft fingers through the pully and cable mechanism. The particle jamming chamber is stiffening to resist external load or freeze the current position of the finger. Figure 6a show the two chambers attached to the two soft fingers in vertical orientation and they are activated to keep the vertical position of the soft fingers. However, Fig. 6b shows the bending situation of the two fingers and they are freezing at that bending position thanks to the particle jamming chambers.

The layer jamming chambers are attached to the two soft fingers to support the current state of the fingers similar to the particle jamming chambers that are presented earlier. Fig. 7a shows the vertical orientation of the combined layer jamming chambers with the soft fingers. However, Fig. 7b shows the bending state of the two fingers while the layer jamming chambers are activated to freeze the bending situation of the fingers.

### 3.4 Proposed controlled stiffness steps using a force sensor

In this section a proposed controlled stiffness strategy using force sensor (FSR) will be presented. The steps will be based on the reading received from the FSR sensor that is attached to the soft finger (Fig. 8). The FSR sensor measures the force when the soft finger is in contact with the object and according to the reading from the FSR the main controller will activate the jamming chamber. The Firstly, the finger will be receiving the movement from the actuator to bend towards the object and hence it is in contact with the object the reading from the FSR will be received by the jamming controller which will activate the chamber by providing signal to the vacuum pressure via solenoid valve to let the jamming chamber activated and freeze the state of the fingers. The schematic diagram of the proposed controller architecture can be seen in Fig. 9.

The relation between the force measured by the FSR sensor and jamming pressure that is to be applied to the jamming chamber can be seen in Fig. 10. It can be assumed that for objects with light objects such as plastic sheet, which can be grasped by using the soft fingers without the need to activate the jamming chamber. Therefore, in this case the FSR reading will measure low contact force between the ball and the soft finger. Table 1 summarizes the activated and non-activated states of the

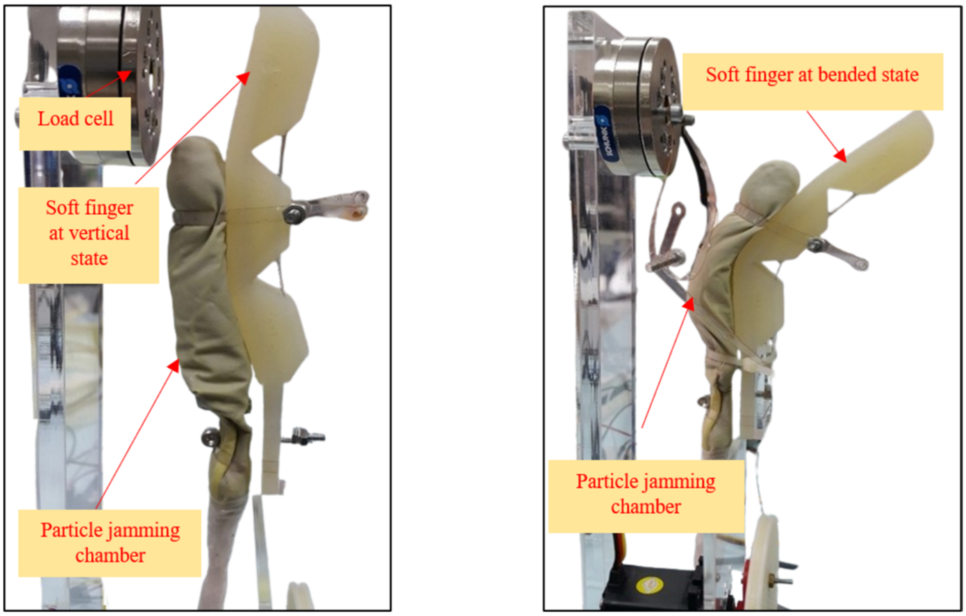


**Fig. 4** Under actuation mechanism combined with particle jamming for soft finger

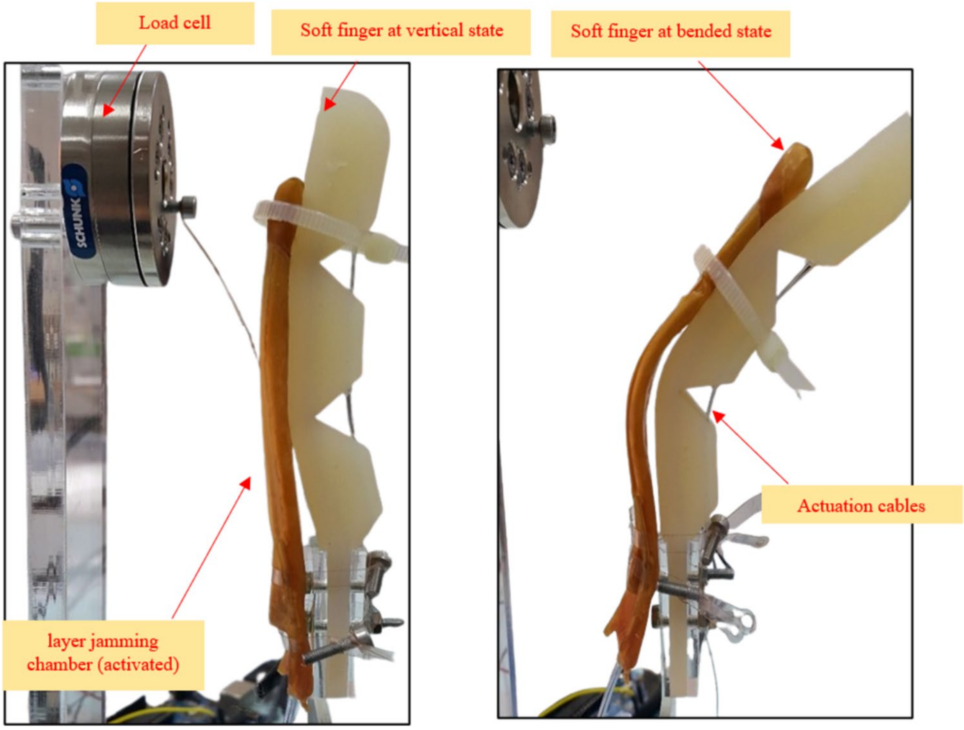


**Fig. 5** Under actuation mechanism combined with layer jamming for soft finger

stiffness jamming controller and the position controller of the gripper system according to different type of objects.

The flow chart of shown in Fig. 11 shows the steps from the start to the end for the stages of grasping the objects. The flow chart starts by providing the required movement to the fingers and the second step after the finger touches the object the FSR sensor measures the force. According to the range of forces stored in the controller, the action will be taken by the controller to activate or non-activate the jamming chamber.

For more clarification, A Matlab/Simulink was used to build a block diagram to show the simple two states of the jamming and an jamming of the chamber along with the movement states of the soft fingers (Fig. 12). The IF statement block was used to compare reading of the FSR sensor with threshold reading and afterwards the action by the main

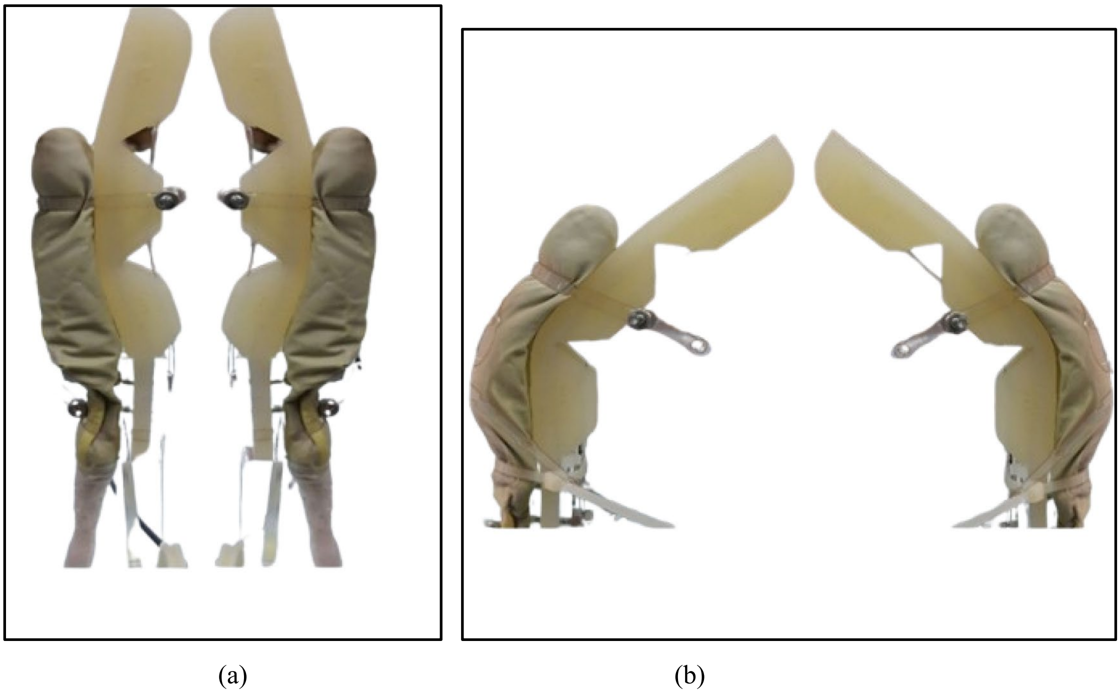

(a) (b)

**Fig. 6** The two fingers gripper combined with particle jamming chambers are oriented in **a** vertical position and **b** bending position

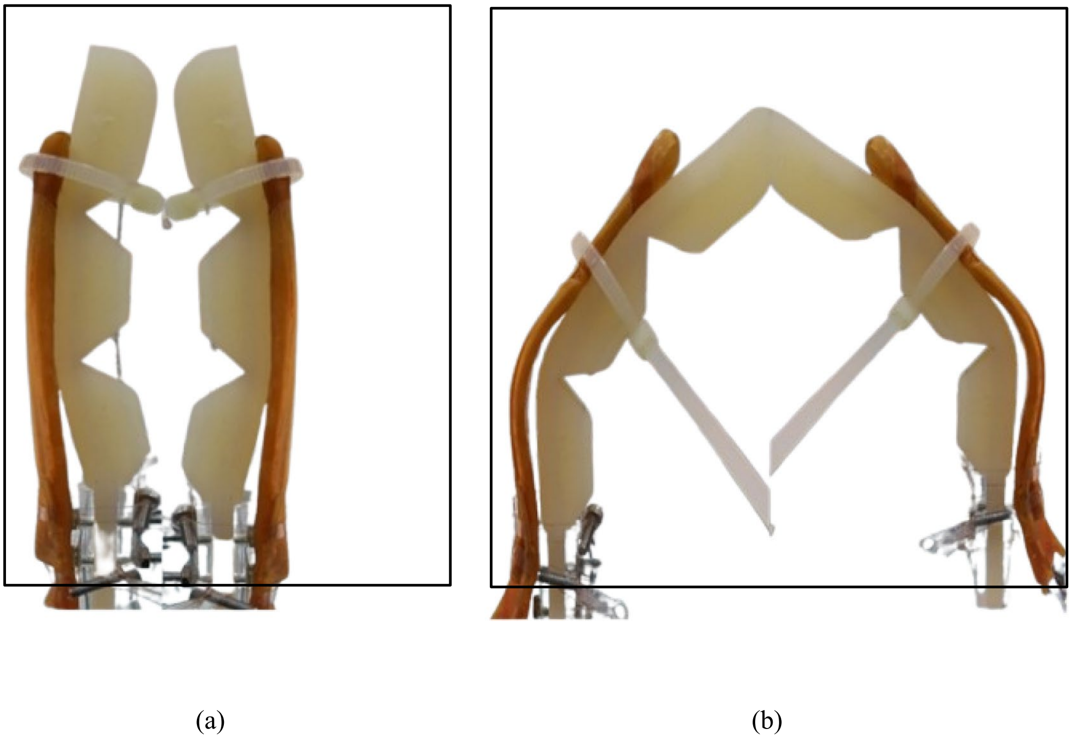

(a) (b)

**Fig. 7** The two fingers gripper combined with layer jamming chambers are oriented in **a** vertical position and **b** bending position

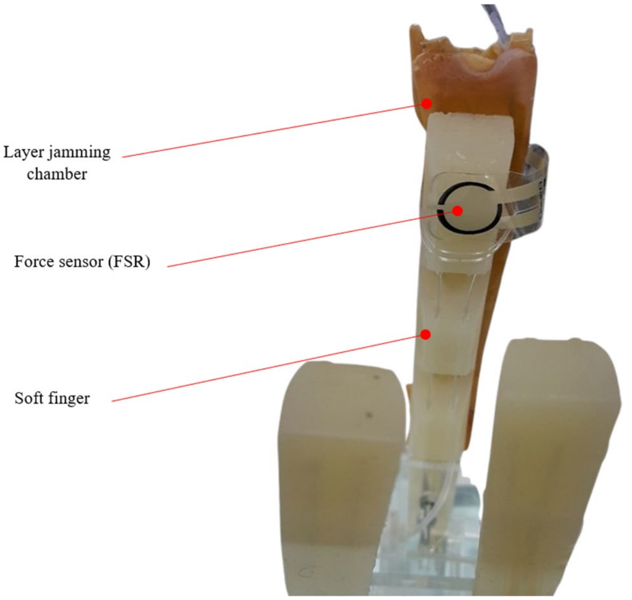


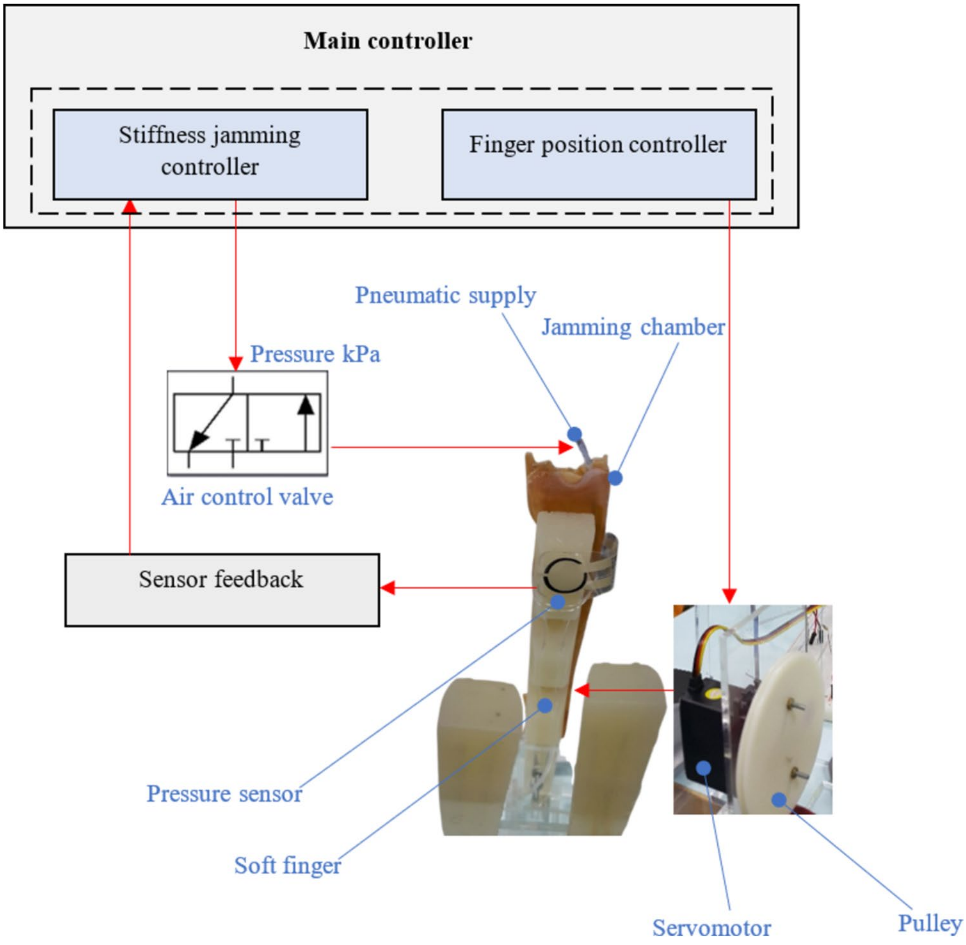
**Fig. 8** Soft finger combined with layer jamming pack and the FSR sensor is placed on the soft finger

controller will be taken. As can be seen in Fig. 12, if the reading of the FSR is 1 Volt while the reference is 0 volt, the jamming pressure will be zero (not activated) and the position controller will be 5 volt it means the servomotor will provide the movement to the fingers. Case number 2, when the reading of the FSR is greater than the reference signal, in this case both jamming pressure will be 20 kPa (activated) and position controller will provide 5 Volt control signals to activate the servo motor to be actuated and consequently provide the movement to the finger.

## 4 Object dynamics

A scenario is presented in which two fingers are placed next to each other to grasp the object. The object dynamics are simplified and depicted as a mass-spring-damper system, with the object in its deformed state illustrated in Fig. 13. To control the finger force (FSR sensor), It was assumed that in contact situation between the finger and the object a definite distance $X_r$ will be obtained according to the finger force Fr (Fig. 13a). The interaction between the finger and the object as can be shown in Fig. 13b, the object is pressed

**Fig. 9** The schematic diagram of the proposed controller architecture



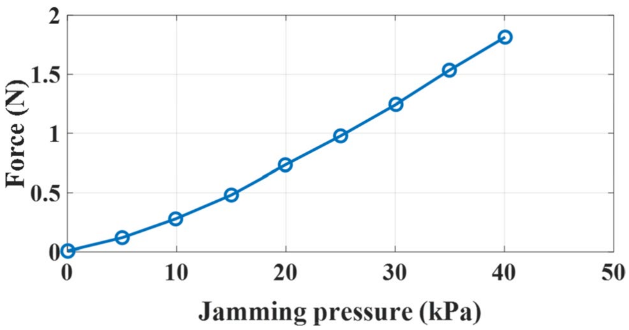


**Fig. 10** Relation between the FSR sensor and the jamming pressure

by the finger and then a deformation $X_{soft}$ will be produced and under this assumption that has been proposed that the exerted force (grasped force) will be by $F_{\mathrm{grasp}}$. As a result, the force exerted by the object and detected by the fingertip sensor is shown in Eq. (1).

$$F_{grasp} = d\dot{x} + k(x - r) \tag{1}$$

To maintain simplicity, it is assumed that the object's shape to be spherical. The interaction forces, denoted as $F_r$ and $F_l$ as can be seen in Eqs. (2) and (3), arising from the object dynamics, are delineated relative to the Cartesian position and velocity of the central mass, and the left and right end-effectors, denoted as $x$ and $\dot{x}$ respectively.

$$Fr = -k_r(l - (x_m - x_l) - d_r(\dot{x}_r - \dot{x}_m) \tag{2}$$

$$F_l = k_l( l - (x_l - x_m) - d_l(\dot{x}_m - \dot{x}_l) \tag{3}$$

where: $F_l$: Left force, $F_r$: Right force, $F_{dkl}$: Force of damper and spring left finger, $F_{dkr}$: Force of damper and spring right finger, $X_m$: object position, $X_r$: Right finger position, $X_l$: Left finger position, $d_{r,l}$: Damping coefficient, $k_{r,l}$: Stiffness coefficient, $m$: Mass of the object, $r$: Radius of the spherical object.

The control scheme can be developed using Matlab/Simulink environment to study the performance of the controller based on different values of distance $X_r$. The closed-loop Simulink block diagram provides a comprehensive visual representation of the entire gripper system, offering insights into its intricate design and functionality (Fig. 14). Each component within the system is interconnected, forming feedback loops that enable dynamic interactions and control mechanisms. The force controller utilizes a PID algorithm to adjust the gripper's performance based on the error signal received. Additionally, the simulation can predict the behavior of the gripper under various grasping conditions, offering valuable insights into its performance characteristics. Moreover, closed loop force Simulink block diagram of different categories of objects is shown in Fig. 15. In order to study the performance of the gripper's force controller, the grasping performance will be examined based on three different types of objects with varying degrees of softness: a sponge, plastic bottles, and a glass cup. Different force profiles will be used for these three objects to study the controller's performance. As a result, this will provide insights about the degree of stiffness according to the rate of softness for each object. The outcomes of the simulation results will be discussed in the Results section, which follows later in the paper.

## 5 Results

### 5.1 Characterization of the of soft finger module

#### 5.1.1 Stiffness for single soft finger module

The definition of stiffness represents an object's ability to resist deformation when subjected to external forces. In this study, stiffness is calculated using a force, denoted as F, that causes a displacement, denoted as X. The measurement of stiffness of the is performed using the setup shown in Fig. 3. As The graph shows a maximum force of 1 N at 20 mm distance as the force increase linearly versus the distance Fig. 16.

#### 5.1.2 Stiffness of single soft finger module combined with particle jamming

In the second mode, the particle jamming chamber was attached to the soft gripper as in Fig. 4. Similar procedure of testing of single finger module was performed in order to get a relation between force versus displacement shown in Fig. 16. As can be noticed from Fig. 16, that there is a

**Table 1** The activated and non-activated states of the stiffness jamming controller and the position controller of the gripper system according to different type of objects

| Object type | FSR reading | Finger movement controller | Jamming controller |
|---|---|---|---|
| Plastic case, DVD disc | ≈ 0 | Activated | Not |
| Plastic bottle, cup | 0- 1 N | Activated | Activated (0- 20 kPa) |
| Tomato, cucumber, Wooden box | More than 1 N | Activated | More than 20 kPa |

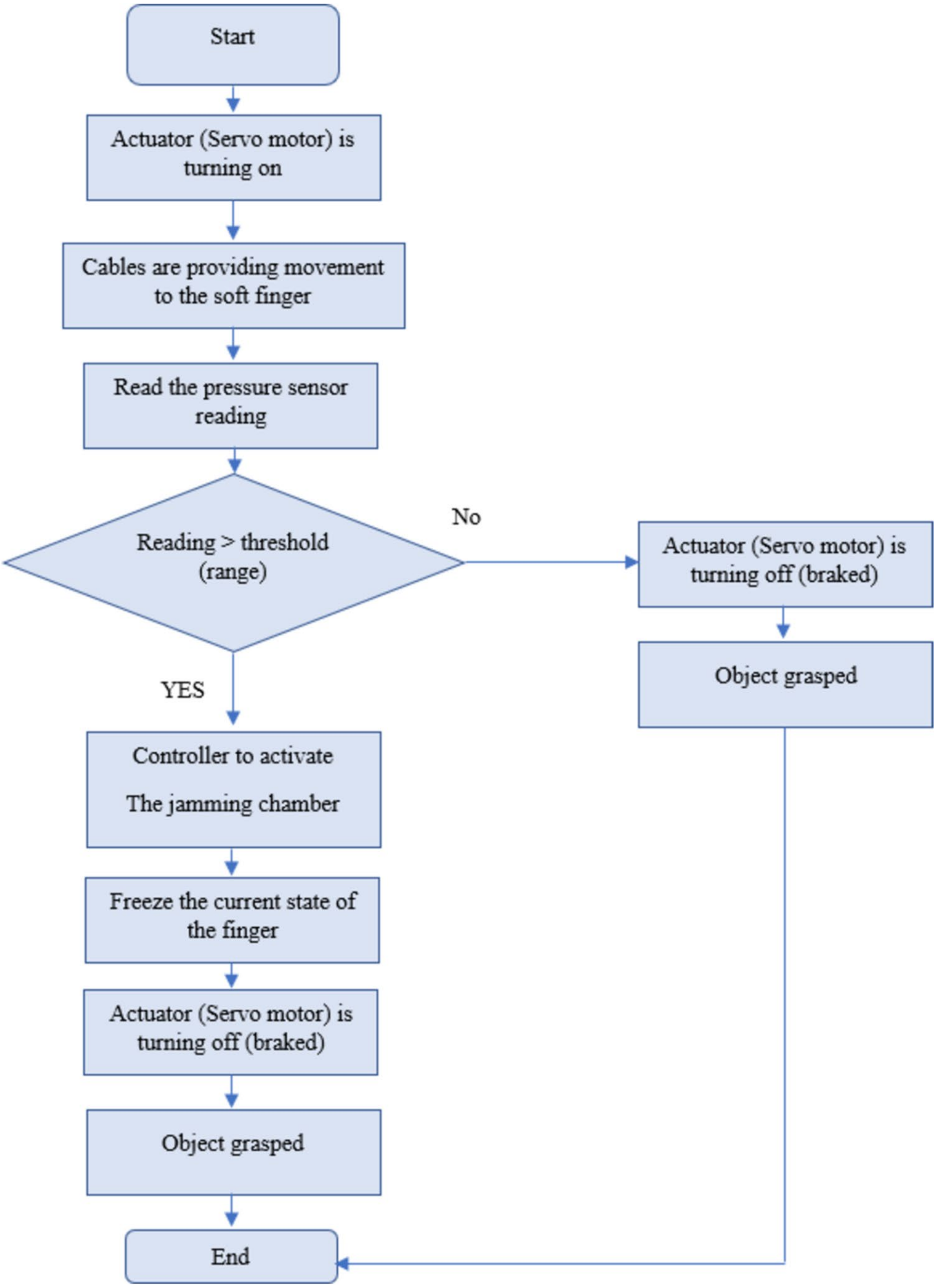


**Fig. 11** Flowchart shows the stages of grasping the objects by soft fingers combined with jamming chambers

proportional relation between force and displacement. However, in the case of attaching the particle jamming chamber, the force is about 1.75 N which is higher than the case of single finger module at the same distance of 20 mm. That is to say that if the particle jamming chamber attached to the soft gripper, the force is improved and becomes higher with an amount of about 0.75 N. Also, simulation of deflection for the particle jamming chamber with the finger is shown in Fig. 16.

### 5.1.3 Stiffness of single soft finger module combined with layer jamming

The plot in Fig. 16 shows the maximum force of 2.25 N at 20 mm distance. It can be noticed that in this case the force is higher than the forces in both previous cases. The layer jamming chamber increases the stiffness of the whole system better than the particle jamming as well as the single soft finger.

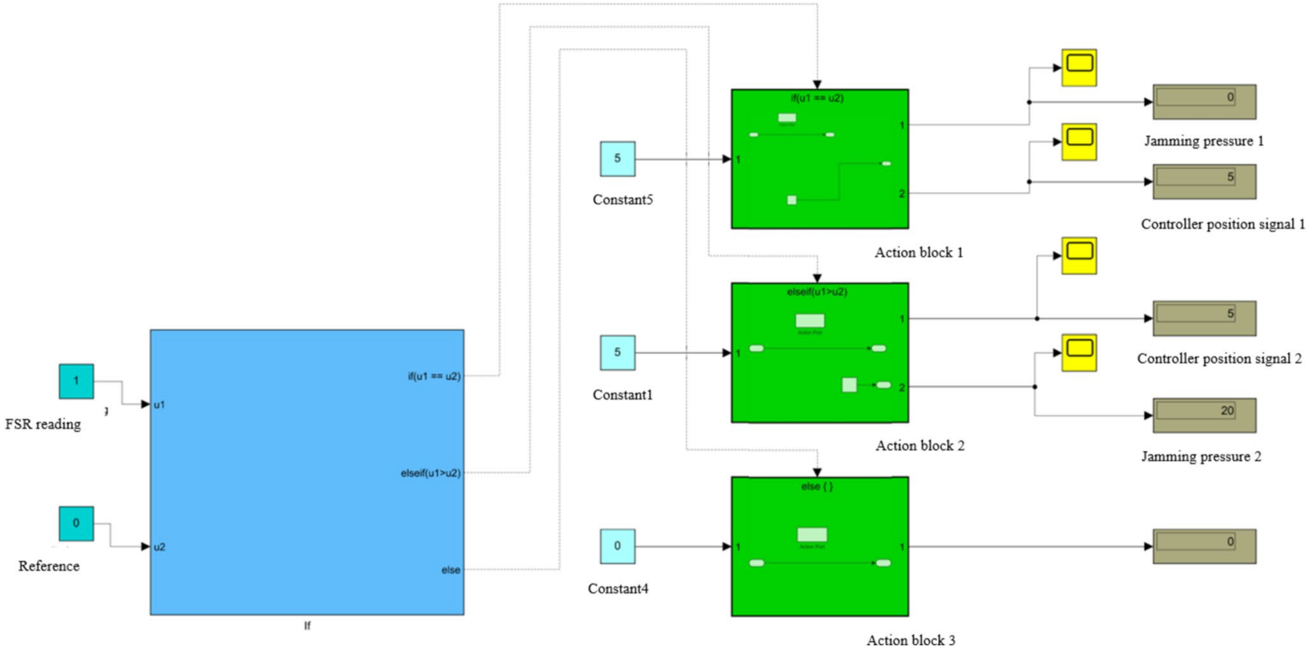


**Fig. 12** A Simulink block diagram illustrating the activation and non-activation of the position and jamming controllers based on two simple conditional states of the main controller action

### 5.1.4 Stiffness calculation

The calculation of the stiffness for each case—single finger module, particle jamming, and layer jamming—can be performed using the force-displacement plots shown in Fig. 16. By determining the slope of the force-displacement curve at certain displacement values, we can represent the stiffness with the slope (k). This is calculated using Hooke's Law as shown in Eq. (4)

$$k = F/X \tag{4}$$

where k is the stiffness, F is the force applied, and X is the resulting displacement.

In this study, three displacement values of 5, 10, and 15 mm were chosen to calculate the stiffness at each case of the soft finger. The stiffness at three different conditions of the soft finger will be calculated according to Eq.uation (4). The calculations of the stiffness for the three different cases are summarized as shown in Table 2.

As can be observed from Table 2, the stiffness of the single finger under both the single condition and particle jamming shows a gradual increase in stiffness values at the three displacement values. This suggests that the relationship between force and displacement is proportional, likely due to the constant structural properties with small deformation. However, the condition of the single finger combined with layer jamming presents interesting stiffness values at displacements of 10 and 15 mm, which are 0.172 and 0.133 respectively. Interestingly, the stiffness value decreases as the displacement increases, causing stiffness modulation which introduces non-linearities in the stiffness response.

### 5.1.5 Response time of the soft finger module

Response time is another means to define the soft finger dynamic response. Understanding the response time is essential for designing control systems that can accurately and efficiently control the gripper's movement. Also, in applications requiring real-time adjustments, such as handling delicate objects, the control system relies on the response time to make quick corrections based on sensor feedback Response time is calculated while the finger's output reaches a specific percentage of output value when a step change is applied to its input. The step input function is applied to the system to determine the behavior and speed of the system in response to a change in input the step force responses of the soft finger at the three different cases are illustrated in Fig. 17. The response time is calculated according to 98% criteria. So, it can be seen in case of soft finger module the response time is about 0.8 s due to an amount of force of 1 N. For the particle jamming chamber that attached with the soft finger and the layer jamming, the response times are 0.75 s and 0.85 s respectively.

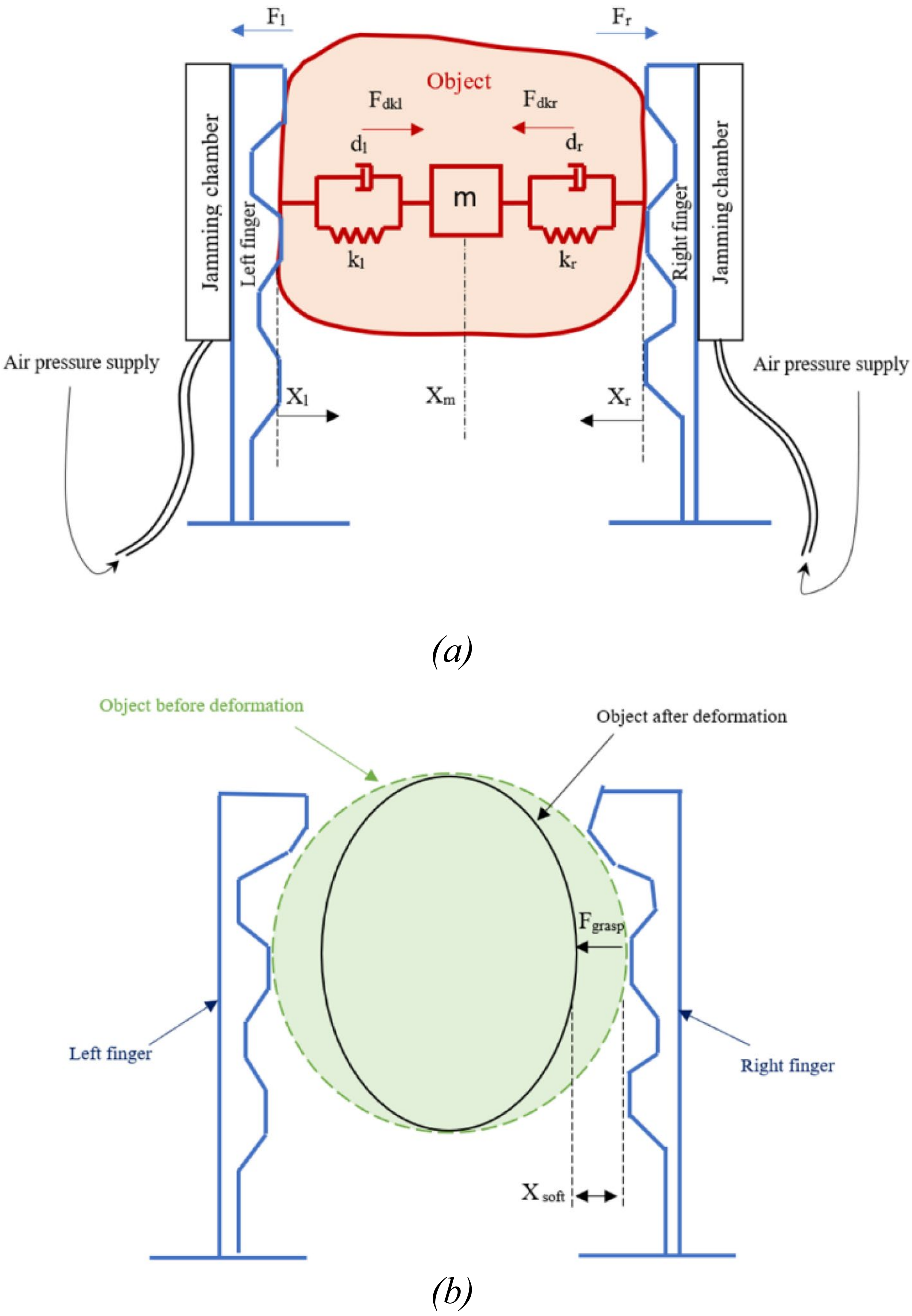


**Fig. 13** **a** Simplified schematic representation of an object grasped by the soft Finger, modelled as a mass-spring-damper system and **b** deformation of the object at grasping state of the fingers

## 5.2 Simulation of the soft gripper

One of the criteria used to determine the characteristics of the gripper's grasping force is the response to step and sinewave force inputs. Therefore, the soft fingers gripper proposed in this work is subjected to a step input force of 2 N, as illustrated in Fig. 18. The simulation at this state is based on the soft gripper, providing insight into the controller's functionality in response to step input grasping force. Additionally, the simulation results demonstrate the performance of the finger force due to environmental interaction (objects). Both the step input and sine wave signal were used to test the controller's functionality at a force value of 2 N. The PID controller was tuned to achieve acceptable performance. The results showed an error of about 0.1 N at the 5-second mark, which was selected as the time period to study the performance of the gripper system.

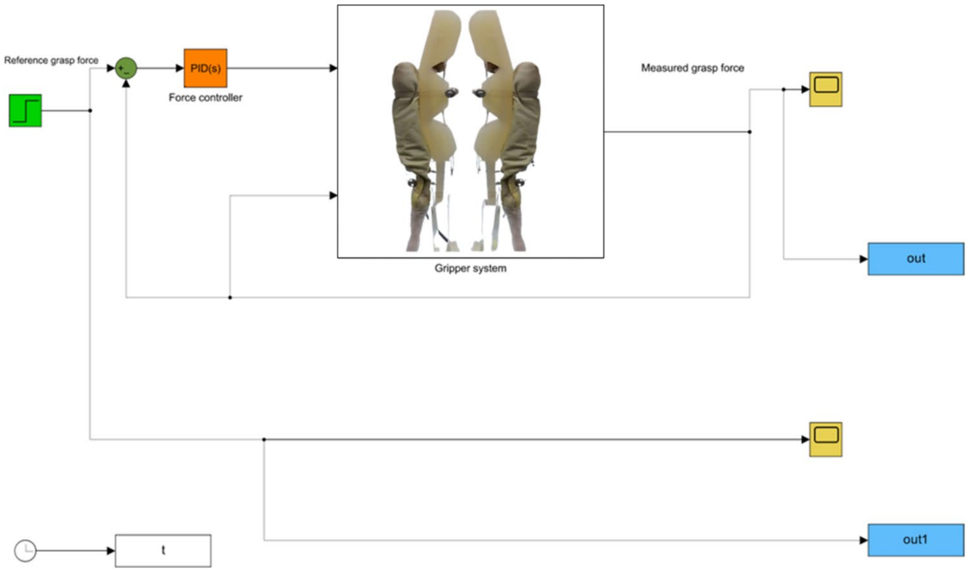


**Fig. 14** Closed-loop force control scheme of the gripper system

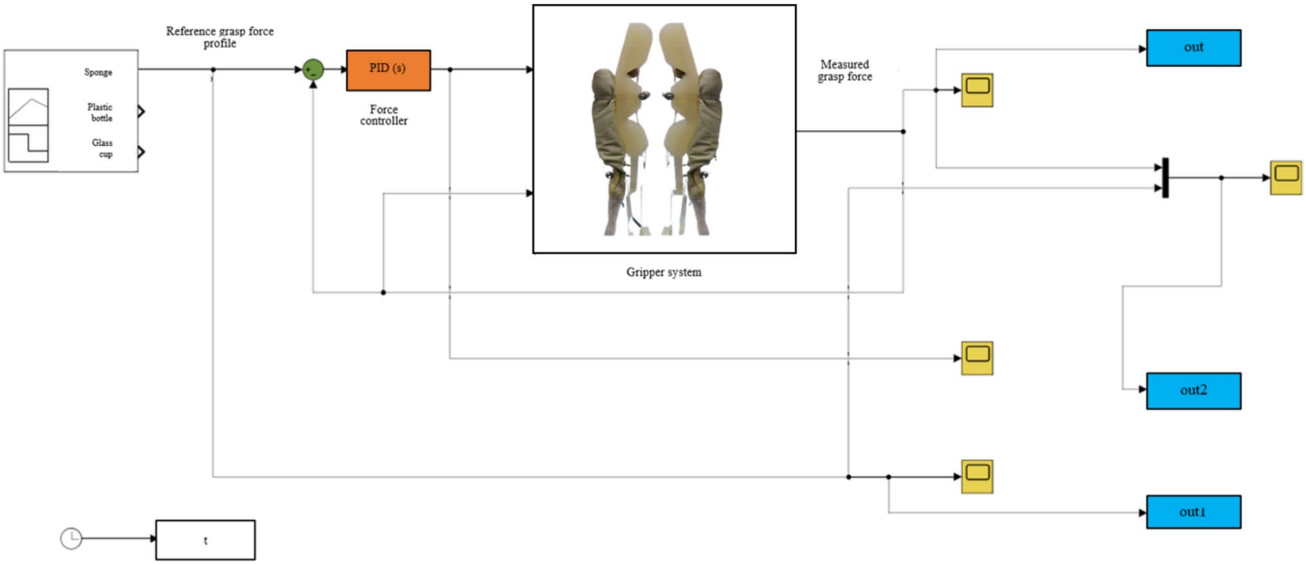


**Fig. 15** Closed loop block diagram of the gripper system at different objects force profile

#### 5.2.1 Force measurement scenario of different objects

The grasping force of the target object is a significant parameter that must be established when the gripper grasps an object. A rigid object, such as a glass cup or metal container, has a high stiffness and will not be distorted by the grabbing force. The upper limit force for this category of items is defined as the maximum limit of the applied force of the robot finger. Soft objects, such as plastic or paper cups, have a medium stiffness and can deform when the grasping force of the robot hand is increased. Because the force that deforms objects is bigger than the lift-off gripping force in this category, the optimal upper limit force is selected to have the smallest difference between the two forces. The third category includes exceedingly soft objects like sponges and other items with little rigidity. A small grabbing force deforms this type of item. Yet, unlike soft things, this distortion is acceptable for the robot hand to maintain a secure grasp even if it produces a minor deformation of the item surface. The idea for our method is that various stiffness objects will have different mechanical responses to the initial touch. As a result, force data for determining stiffness is gathered and processed. Force curves response of different categories of objects can be shown in Fig. 19.

The output simulated output force. The Results of the simulation of the gripper finger using PID controller can be

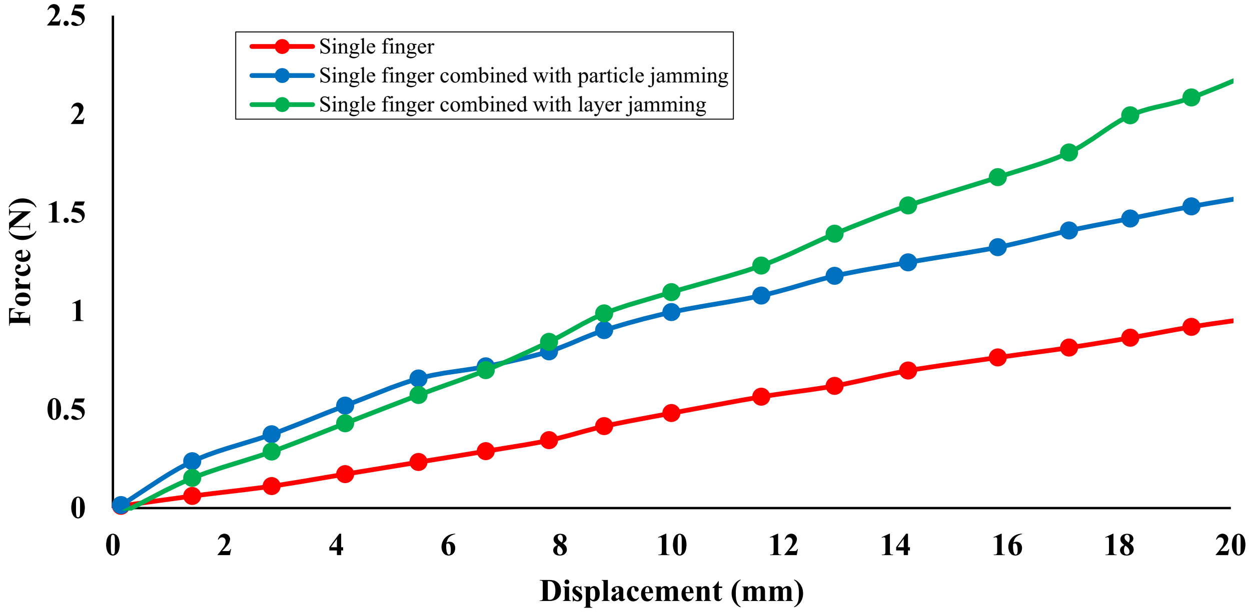


**Fig. 16** Stiffness of the soft finger at three different conditions, Single module soft finger, single module soft finger combined with particle jamming, and single module soft finger combined with layer jamming

**Table 2** Stiffness values of a single finger under three different conditions, measured at various displacement values

| Displacement (mm) | Stiffness (N/mm) | | |
|---|---|---|---|
| | Single soft finger | Soft finger combined with particle jamming | Soft finger combined with layer jamming |
| 5 | 0.04 | 0.102 | 0.244 |
| 10 | 0.05 | 0.058 | 0.172 |
| 15 | 0.051 | 0.085 | 0.133 |

seen in Fig. 20. The Simulated system attempts to follow the reference profile force of sponge, plastic bottle, and the glass cup respectively as shown in Fig. 20a–c.

## 6 Discussion

Gripper actuation is a crucial component in the field of robotic grippers, as it provides movement to the gripper fingers. However, certain objects require an adaptable

**Fig. 17** Step response for the soft finger module, soft finger with particle jamming, and soft finger with layer jamming

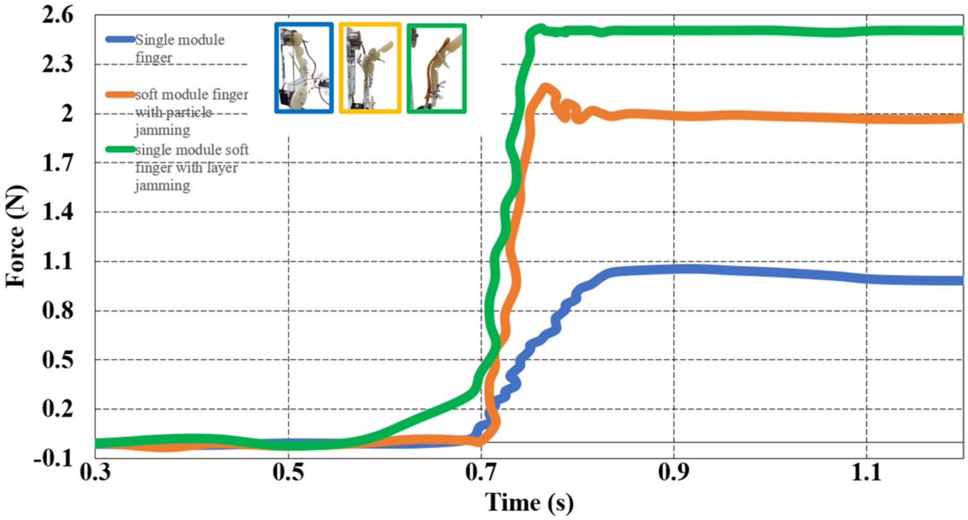
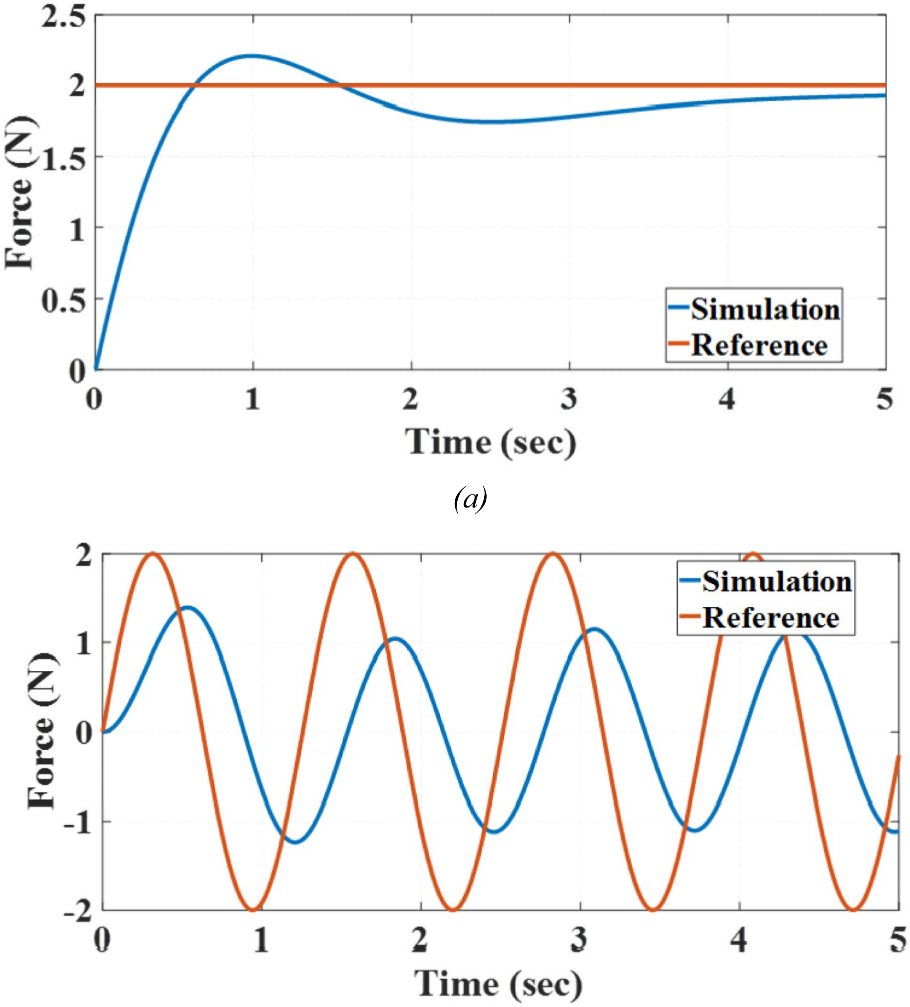


**Fig. 18** Force simulation results **a** Force simulation results against a reference step input value of 2 N, **b** force simulation results against a reference sinewave value of 2 N



*(a)*

*(b)*

grasping mechanism. In such cases, actuation technology alone may not be sufficient and can be combined with a stiffness mechanism to provide adaptability while grasping soft or hard objects. In order to link the outcomes of the paper to research question 1, the developed soft finger module used the simple actuation technology that is driven by motor and cable mechanism which is easy to operate and control using a microcontroller, and it requires less power. The jamming chambers, which utilize both particle and layer jamming, are presented in this paper. They have been attached and detached from the soft finger using cable ties. However, it is believed that the attachment and detachment of the jamming chambers to the soft finger require further improvement in the future which will be considered.

For research question 2, the effectiveness of jamming chambers is essential when needed. In some scenarios, it is enough to utilize the soft finger that is actuated by the motor and cable mechanism. However, in cases such as grasping objects of various degrees of softness, the activation of the jamming chamber will vary the stiffness and enhance the control of the object's grasp. The paper proposed a scenario of how to control the jamming chambers based on pneumatic pressure using a force sensor. A full simulated block diagram was presented, illustrating the activation and non-activation of the jamming chambers based on two simple conditional states. This proposed control scenario will be beneficial for researchers to understand the physical operation of activating and deactivating the jamming chambers when required. The third research question addressed in the paper presents a proposed closed-loop system utilizing a PID controller to regulate the grasping force of the soft gripper. The system was tested with three distinct target objects: a sponge, a plastic bottle, and a glass cup. In all three cases, the output forces successfully followed the reference force. However, to generalize the grasping performance of the soft gripper, it is advisable to increase the variety of objects tested. In order to link the results with the design requirements depicted in Fig. 1, a prototype of the soft finger module was

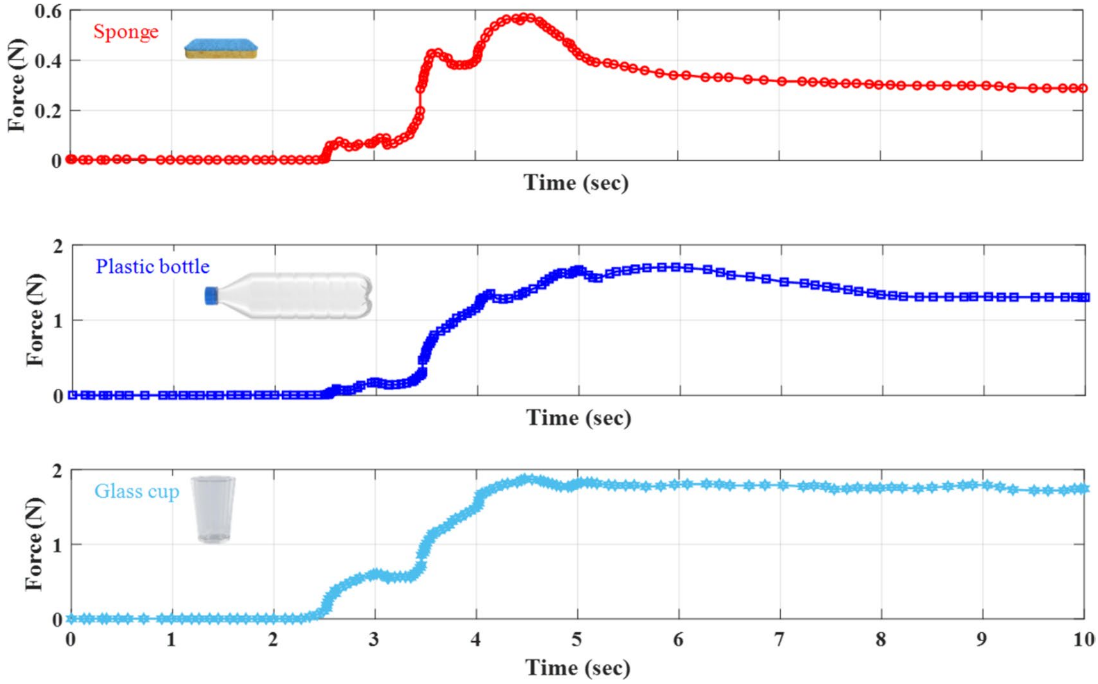


**Fig. 19** Comparison of Force response of objects with different shape and surface

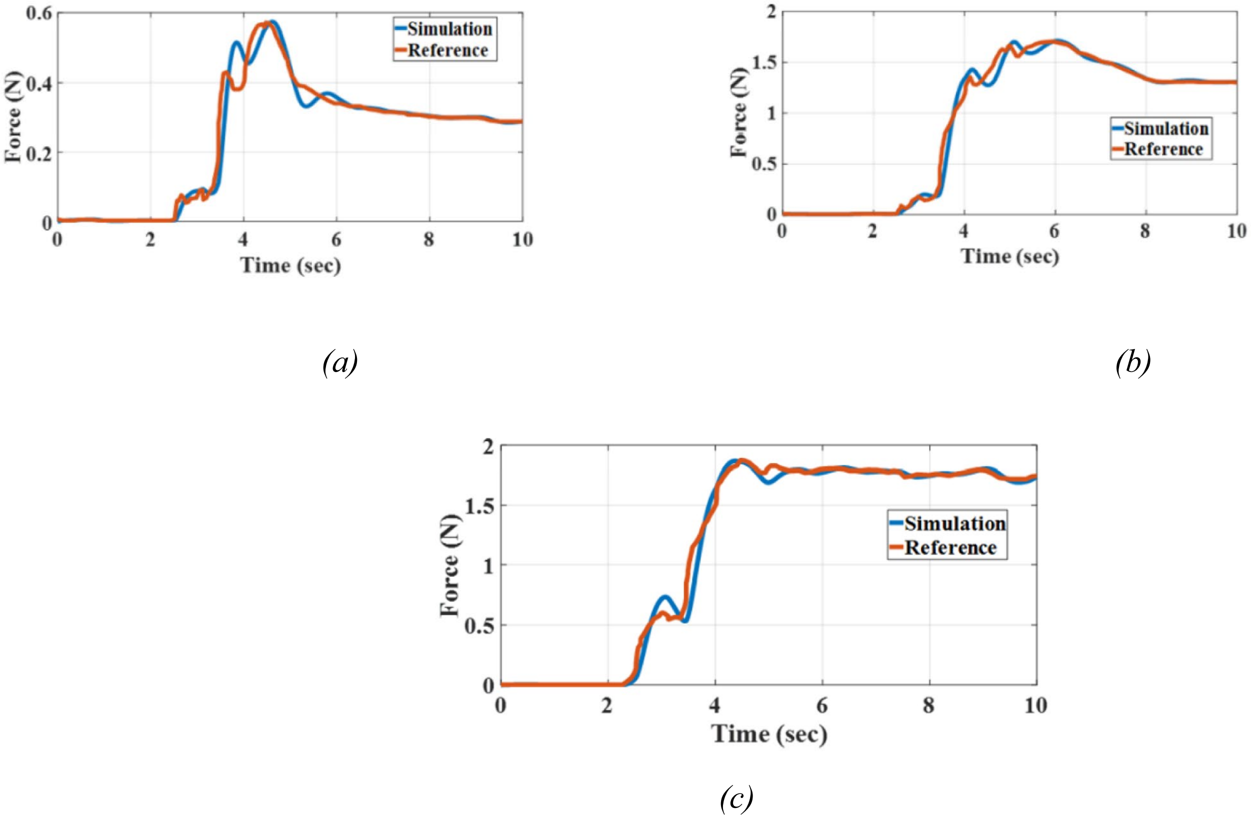


**Fig. 20** Results of the simulated gripper system with different force profile of different objects, **a** Sponge, **b** Plastic bottle, **c** Glass cup

developed. The stiffness mechanisms of particle and layer jamming were employed to control the stiffness of the soft finger. These mechanisms were easily attached to the soft finger. The jamming mechanism chambers were affixed to the soft finger, facilitating stiffness adjustments as needed. The design and development of these jamming chambers were straightforward, resulting in less complexity in control at this stage.

A control system architecture was proposed for managing the stiffness chambers using a simple force sensor (FSR). A flowchart was also presented, illustrating the sequence of steps for grasping objects using the controlled stiffness architecture. Additionally, a simulation was provided, demonstrating the activation and deactivation of the position and jamming controllers, based on two simple conditional states of the main control action. Regarding response time, the rise time for the soft finger was measured under three scenarios: single module, particle, and layer jamming. An average value of 0.75 s was observed, aligning with the design specifications. The proposed soft gripper force control was tested on three different objects of varying shapes and degrees of softness. However, the grasping force for these three objects was found to range from 0 to 2 N. This indicates that testing of the soft gripper with a variety of objects is suggested, to maximize the range of the grasping force and meet the overall system specifications.

## 7 Conclusions

This paper presented a soft finger module was developed for this purpose. This module is attached to both particle and layer jamming mechanisms. A proposed simulation to control the jamming chambers was introduced based on two simple conditional states of the main controller action. The performance of soft finger module setup was evaluated. Both experimental tests and simulations were conducted for this assessment. Also, the paper presented a soft gripper module. It can interact with three objects: a sponge, a plastic bottle, and a glass cup. The results provide insights into the effectiveness of the model. This contributes to the field of smart controlled grippers. The findings can be applied to improve future designs. The paper thus offers valuable information for researchers and practitioners.

The proposed design of a combination of granular method and cable mechanisms have been prototyped to proof the concept and tested to assess their both static and dynamic performances. The soft finger that is driven by cables and combined with both particle and layer jamming mechanism in order to vary the stiffness was tested in terms of stiffness, force, and time response. Moreover, a simulation of the soft finger was conducted in order to predict the deflection at different applied forces. The maximum force achieved with a combined approach has been increased by 125% from 1 Newton to 2.25 Newtons. The response time with current experimental setting is under 0.85 second. This response time is still slow for time critical and rapid response application. it is therefore necessary to extend the work to address this in future. Although the percentage increase of the maximum force achieved is promising, the overall force is still small and further investigation is requited to improve this for applications where the large amount of forces is involved. Moreover, modelling, simulation, and control of the overall gripper system have been presented and force of grasping has been tested with different objects such as sponge, plastic bottle, and glass cup.

**Author contributions** The paper introduces a smart stiffness mechanism for soft gripper fingers that has the potential to improve the grasping abilities of robotic systems. The smart stiffness mechanism is based on combining the under-actuated cable-driven mechanism of a soft gripper finger with particle and layer jamming mechanisms. This creates a new grasping function with variable stiffness for different manipulation requirements.

**Data availability** No datasets were generated or analysed during the current study.

## Declarations

**Conflict of interest** The authors declare no competing interests.

**Ethical approval** None.

## References

Abu Bakar, R.B., Watada, J.: A bio-soft computing approach to re-arrange a flexible manufacturing robot. In: Apolloni, B., Howlett, R.J., Jain, L. (eds.) Knowledge-Based Intelligent Information and Engineering Systems: KES 2007 - WIRN 2007, Pt III, Proceedings. p. 308-315, (2007)

Amend, J.R., et al.: A positive pressure universal gripper based on the jamming of granular material. IEEE Trans. Rob. **28**(2), 341–350 (2012)

Ansari, Y., et al.: Dynamic walking with a soft limb robot. In: Wilson, S.P., et al., (eds.) Biomimetic and Biohybrid Systems, Living Machines. 2015. Lecture Notes in Computer Science, vol 9222. Springer, Cham. (2015). https://doi.org/10.1007/978-3-319-22979-9_2

Bogue, R.: Flexible and soft robotic grippers: the key to new markets? Ind. Robot Int. J. **43**(3), 258–263 (2016)

Chen, Q., Schott, D., Jovanova, J.: Conceptual design of a novel particle-based soft grasping gripper. J. Mech. Robot. **16**(5), 051004. https://doi.org/10.1115/1.4062647 (2024)

Cheng, P., et al.: Eccentric high-force soft pneumatic bending actuator for finger-type soft grippers. J. Mech. Robot. **14**(6), 060908 (2022)

Cheong, H.R., et al.: Wireless-powered electroactive soft microgripper. Smart Mater. Struct. **27**(5), 055014 (2018)

Cianchetti, M., et al.: Biomedical applications of soft robotics. Nat. Rev. Mater. **3**(6), 143–153 (2018)

Cianchetti, M., et al.: STIFF-FLOP surgical manipulator: mechanical design and experimental characterization of the single module. In: 2013 IEEE/RSJ International Conference on Intelligent Robots and Systems. IEEE (2013)

Deimel, R., Brock, O.: A novel type of compliant and underactuated robotic hand for dexterous grasping. Int. J. Robot. Res., **35**(1-3), 161–185. (2015a)

Deimel, R., Brock, O.: Soft hands for reliable grasping strategies. In: Soft Robotics, Berlin; Heidelberg, Springer, pp. 211–221. Springer (2015b)

Deimel, R., Brock, o.: 18 soft hands for reliable grasping strategies. In: Soft Robotics: Transferring Theory to Application, p. 211 (2015c)

Dong, H., et al.: Grasp analysis and optimal design of robotic fingertip for two tendon-driven fingers. Mech. Mach. Theory **130**, 447–462 (2018)

El-Sayed, A., et al.: Development of a micro-gripper using piezoelectric bimorphs. Sensors **13**(5), 5826–5840 (2013)

El-Sayed, A., Hamzaid, N., Abu Osman, N.: Piezoelectric bimorphs' characteristics as in-socket sensors for transfemoral amputees. Sensors **14**(12), 23724–23741 (2014)

Fitzgerald, S.G., Delaney, G.W., Howard, D.: A review of jamming actuation in soft robotics. In: Actuators. MDPI (2020)

Gao, Y., et al.: A novel variable stiffness compliant robotic gripper based on layer jamming. J. Mech. Robot. **12**(5), 051013 (2020)

Hassan, T., et al.: Design and development of a bio-inspired, under-actuated soft gripper. In: 2015 37th Annual International Conference of the IEEE Engineering in Medicine and Biology Society. IEEE, p. 3619–3622 (2015)

Hayashibara, Y.: Study on a variable stiffness mechanism using wire spring. J. Robot. Mechatron. **20**(2), 296 (2008)

Hou, T., et al.: Design and experiment of a universal two-fingered hand with soft fingertips based on jamming effect. Mech. Mach. Theory **133**, 706–719 (2019)

Hu, J., Xiao, C., Wen, T.: A novel tunable stiffness mechanism using filament jamming. J. Mech. Robot. **13**(6), 061015 (2021)

Hussain, I., et al.: Compliant gripper design, prototyping, and modeling using screw theory formulation. Int. J. Robot. Res. **40**(1), 55–71 (2021)

In, H., et al.: Jointless structure and under-actuation mechanism for compact hand exoskeleton. In: 2011 IEEE International Conference on Rehabilitation Robotics. IEEE (2011)

Jafari, A., et al.: A new actuator with adjustable stiffness based on a variable ratio lever mechanism. IEEE/ASME Trans. Mechatron. **19**(1), 55–63 (2014)

Jujjavarapu, S.S., et al.: Variable stiffness mechanism for suppressing unintended forces in physical human–robot interaction. J. Mech. Robot. **11**(2), 020915 (2019)

Lei, J., et al.: Design and manufacture of a flexible pneumatic soft gripper. Appl. Sci. **12**(13), 6306 (2022)

Li, Y., et al.: Passive particle jamming and its stiffening of soft robotic grippers. IEEE Trans. Rob. **33**(2), 446–455 (2017)

Li, Y., Chen, Y., Li, Y.: Pre-charged pneumatic soft gripper with close loop control. IEEE Robotics and Automation Letters **4**, 1402–1408 (2019)

Lien, T., Caldwell, D.: Gripper technologies for food industry robots. In: Robotics and Automation in the Food Industry: Current and Future Technologies, p. 143 (2012)

Liu, M., et al.: A novel design of shape-memory alloy-based soft robotic gripper with variable stiffness. Int. J. Adv. Rob. Syst. **17**(1), 1729881420907813 (2020)

Luo, M.: Finger orientation for robotic hands. In: Grasping in Robotics, pp. 159–188. Springer (2013)

Lv, Z., et al.: Design and performance analysis of wavy nonrotating pneumatic soft actuator. J. Mech. Robot. **16**(2), 021011 (2024)

Manti, M., et al.: A bioinspired soft robotic gripper for adaptable and effective grasping. Soft Rob. **2**(3), 107–116 (2015a)

Manti, M., et al.: An under-actuated and adaptable soft robotic gripper. In: Wilson, S.P., et al., (eds.) Biomimetic and Biohybrid Systems, Living Machines. p. 64–74 (2015b)

Manti, M., et al.: An under-actuated and adaptable soft robotic gripper. In: Conference on Biomimetic and Biohybrid Systems. Springer (2015c)

Manti, M., Cacucciolo, V., Cianchetti, M.: Stiffening in soft robotics: a review of the state of the art. IEEE Robot. Autom. Mag. **23**(3), 93–106 (2016)

Meng, L., et al.: A mechanically intelligent crawling robot driven by shape memory alloy and compliant bistable mechanism. J. Mech. Robot. **12**(6), 061005 (2020)

Narang, Y.S., Vlassak, J.J., Howe, R.D.: Mechanically versatile soft machines through laminar jamming. Adv. Funct. Mater. **28**(17), 1707136 (2018)

Nguyen, N.D., et al.: Manipulating soft tissues by deep reinforcement learning for autonomous robotic Surgery. arXiv preprint arXiv:1902.05183, (2019)

Pan, M., et al.: Soft actuators and robotic devices for rehabilitation and assistance. Adv. Intell. Syst. **4**(4), 2100140 (2022)

Petković, D., Pavlović, N.: A new principle of adaptive compliant gripper. In: Mechanisms, Transmissions and Applications, pp. 143–150. Springer (2012)

Raatz, A.S.B., Runge, G., Bruns, C., Borchert, G.: Opportunities and Challenges for the Design of Inherently Safe Robots, in Soft Robotics - Transferring Theory to Application, p. 181191. Springer Vieweg, Berlin (2015)

Ranzani, T., et al.: A bioinspired soft manipulator for minimally invasive surgery. Bioinspir. Biomim. **10**(3), 035008 (2015)

Rus, D., Tolley, M.T.: Design, fabrication and control of soft robots. Nature **521**(7553), 467–475 (2015)

Sadati, S.H., et al.: Stiffness control of soft robotic manipulator for minimally invasive surgery (MIS) using scale jamming. In: International Conference on Intelligent Robotics and Applications. Springer (2015)

Shintake, J., et al.: Soft robotic grippers. Adv. Mater. **30**(29), 1707035 (2018)

Smith, K.K.: Trunks, tongues, and tentacles: moving with skeletons of muscle. Am. Sci. **77**, 29–35 (1989)

SOFT Robot WALKS: Chem. Eng. News **89**(49), 36–36 (2011)

Tadesse, Y., Hong, D., Priya, S.: Twelve degree of freedom baby humanoid head using shape memory alloy actuators. (2011)

Wall, V., Deimel, R., Brock, O.: Selective stiffening of soft actuators based on jamming. In: 2015 IEEE International Conference on Robotics and Automation (ICRA). IEEE (2015), pp. 252–257.

Wang, T., et al.: Electrostatic layer jamming variable stiffness for soft robotics. IEEE/ASME Trans. Mechatron. **24**, 424–433 (2019)

Wang, Z., Hirai, S.: A soft gripper with adjustable stiffness and variable working length for handling food material. In: 2018 IEEE International Conference on Real-time Computing and Robotics (RCAR). IEEE (2018)

Wei, Y., et al.: A novel, variable stiffness robotic gripper based on integrated soft actuating and particle jamming. Soft Rob. **3**(3), 134–143 (2016)

Wei, Y., et al.: A novel, variable stiffness robotic gripper based on integrated soft actuating and particle jamming. Soft Robot. **3**, 134–143 (2016)

Yang, Y., et al.: Novel design and three-dimensional printing of variable stiffness robotic grippers. J. Mech. Robot. **8**(6), 061010 (2016)

Zeng, X., Su, H.-J.: A high performance pneumatically actuated soft gripper based on layer jamming. J. Mech. Robot. **15**(1), 014501 (2023)

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