machines

Review

Application of Soft Grippers in the Field of Agricultural Harvesting: A Review

Daode Zhang [1,2], Wei Zhang [2,*], Hualin Yang [2] and Haibing Yang [1]

[1] School of Mechanical Engineering, Hubei University of Technology, Wuhan 430068, China; 19951044@hbut.edu.cn (D.Z.); hghb.yang@gmail.com (H.Y.)
[2] School of Mechanical and Electrical Engineering, Qingdao University of Science and Technology, Qingdao 266061, China; yanghl@qust.edu.cn
* Correspondence: w.zhang@mails.qust.edu.cn

Abstract: This review summarizes the important properties required for applying soft grippers to agricultural harvesting, focusing on their actuation methods and structural types. The purpose of the review is to address the challenges of limited load capacity and stiffness, which significantly hinder the broader application of soft grippers in agriculture. This paper examines the research progress on variable stiffness methods for soft grippers over the past five years. We categorize various variable stiffness techniques and analyze their advantages and disadvantages in enhancing load capacity, stiffness, dexterity, degree of integration, responsiveness, and energy consumption of soft grippers. The applicability and limitations of these techniques in the context of agricultural harvesting are also discussed. This paper concludes that combined material variable stiffness technology with a motor actuation claw structure in soft grippers is better suited for agricultural harvesting operations of woody crops (e.g., apples, citrus) and herbaceous crops (e.g., tomatoes, cucumbers) in unstructured environments.

Keywords: soft grippers; structure design; actuation; variable stiffness; agricultural harvesting

Academic Editor: Hermes Giberti

Received: 28 November 2024
Revised: 9 January 2025
Accepted: 10 January 2025
Published: 14 January 2025

Citation: Zhang, D.; Zhang, W.; Yang, H.; Yang, H. Application of Soft Grippers in the Field of Agricultural Harvesting: A Review. *Machines* **2025**, *13*, 55. https://doi.org/10.3390/machines13010055

1. Introduction

Robotics was initially developed to replace human labor in repetitive and hazardous tasks, and the gripper is an important component in these tasks [1]. Traditional rigid grippers have standardized drive structures and precise motion control. They are better suited to high-intensity tasks compared to humans. However, these grippers face challenges in the unstructured environments of agricultural harvesting. They struggle to navigate narrow gaps for crop grasping and picking. They are also prone to collisions, which can damage their structures and harm crops [2–6]. Soft grippers, as a complement to rigid grippers, offer better human–robot interaction and environmental adaptability. This is due to their flexible designs and low-modulus materials [7]. Unlike rigid grippers, soft grippers represent a new generation of engineered systems. They are used in various fields, such as disaster rescue, exploration, rehabilitation training, and agricultural harvesting [8,9]. The development of soft grippers is also extending automation technologies from industrial settings to natural environments.

Although significant progress has been made in the design, control, and sensing of soft grippers, their widespread application remains limited. This is particularly true in the field of agricultural harvesting [10]. The biggest challenge is achieving non-destructive harvesting of crops using soft grippers. To handle crops of various shapes and weights, soft grippers must possess good load capacity, radial stiffness, dexterity, and control stability [11]. For harvesting clustered fruits, such as citrus and apples, soft grippers also need active obstacle avoidance capabilities and compact structures [12].

This paper reviews the research progress of soft grippers over the past five years. It summarizes the performance characteristics of soft grippers with different actuation methods and structural types. The advantages and disadvantages of their application in agricultural harvesting are also discussed. In addition, this paper outlines the performance requirements for using soft grippers in agricultural picking. It classifies and summarizes variable stiffness techniques designed to enhance the load capacity of soft grippers. The advantages and disadvantages of different variable stiffness methods are analyzed.

2. Characteristics of Different Actuation Methods and Structures of Soft Grippers

The actuation is the core hardware of a soft gripper. It directly determines a gripper's action mode, load capacity, response speed, control stability, and dexterity. A reasonable choice of actuation method and flexible structure design can greatly enhance the soft gripper's performance. Existing actuation methods for soft grippers can be divided into four categories, while structural types fall into two categories, as shown in Figure 1. The actuation methods comprise fluid actuation, smart material actuation, motor actuation, and tendon actuation [13]. Fluid actuation consists of hydraulic and pneumatic artificial muscle actuation. It is the most widely used method in engineering applications [14,15]. Smart material actuation includes magnetic field actuation, thermal material actuation, photosensitive material actuation, and dielectric elastomer actuation [16]. This actuation method minimizes the actuator size, making it suitable for creating various micro-structures of soft grippers. Smart materials differ from traditional metals, plastics, or silicone materials in that they can be activated and respond to external stimuli, such as electricity, heat, magnetism, and light, producing motions such as bending, elongation, and twisting. They are commonly used to actuate miniature soft robots and soft grippers in general, and can also function as sensors. However, due to limitations in their material properties, smart materials tend to perform relatively poorly when used as actuators for soft grippers [17]. Motor actuation combines the flexibility, good human–robot interaction, and environmental adaptability of soft grippers with the high precision and stability of traditional rigid grippers [18,19]. However, the challenge is that the motors are bulky and can reduce the suppleness of soft grippers. This increases the complexity of the soft gripper's structural design. Tendon actuation is mainly used to actuate the redundant degree of freedom grippers, which can better adapt to the shape of the objects they grasp during use [20]. The structural design of soft grippers is generally categorized into claw and closed structures [21–23]. Claw structures are characterized by high dexterity and the ability to adapt to the contour and size of objects, and offer various grasping and picking strategies for the same crop [24]. In contrast, closed structures provide higher load capacity and stiffness than do claw structures.

In the remainder of this paper, soft grippers are classified according to their different structural designs and actuation methods. The current status of research on soft grippers of different design types and their applications in the field of agricultural harvesting are analyzed through a summary of published literature. The analysis focuses on the required performance of soft grippers for agricultural harvesting.

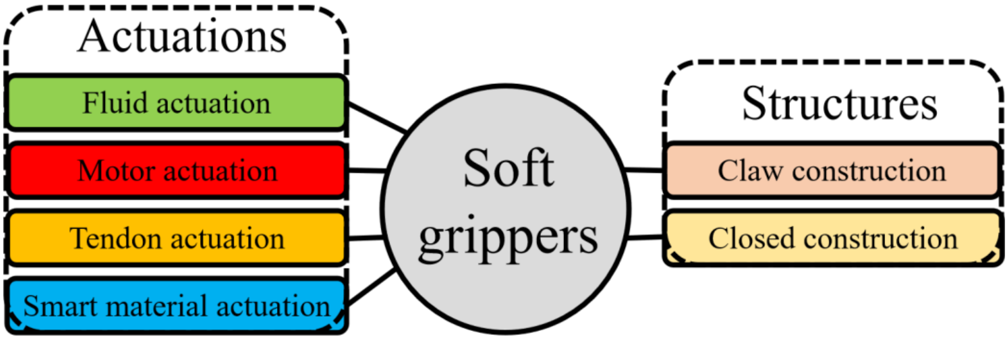

Figure 1. Summary of classification methods of soft grippers.

2.1. *Claw Structure Soft Grippers*

2.1.1. Claw Structure Soft Grippers with Fluid Actuation

Fluid actuation is generally categorized into hydraulic actuation and pneumatic artificial muscle actuation. Both of these are used to realize the bending, expanding, and contracting motions of soft grippers by adjusting the fluid pressure and unit flow rate [24]. Both of these have good low stiffness characteristics and fault tolerance. However, in practice, considering the load ratio and response speed of soft grippers, most of the fluid actuators are pneumatic artificial muscle actuation [25].

Hohime et al. [26] developed a three-finger gas-actuated soft gripper to minimize mechanical damage caused during apple picking, as shown in Figure 2a. The three-finger structure was distributed centrosymmetrically, with two by two spacing of 120°. The three fingers were designed with two short structures and one long structure to increase the wrapping rate of the apples and make the fingers more adaptable to the size differences of apples. The experiment showed that the maximum pull force that the soft gripper can provide is 100.28 ± 4.73N. Fan et al. [27] investigated two gripping modes, vertical and horizontal, as well as four picking modes, vertical pulling, horizontal pulling, vertical-rotary pulling, and horizontal-rotary pulling, of a three-finger soft gripper, as shown in Figure 2b. The experiment showed that the lowest three-finger grip force required for horizontal-rotational pull picking under horizontal grasping conditions was 10.33 N. Wang et al. [12] designed a four-finger soft gripper for apple picking, as shown in Figure 2c. The robot structure consists of four tapered soft fingers and a multi-modal suction cup. The suction cup provides suction force, which improves the gripping stability of the soft gripper during apple picking. Separation of the apple from the branch is achieved by torsion–tension motion. Experimentally, it can be determined that the detachment, damage and harvesting rates of this soft gripper reached 75.6%, 4.55% and 70.77%, respectively. Becker et al. [28] designed a soft gripper based on collective mechanics to realize adaptive grasping without sensing, planning, and feedback, as shown in Figure 2d. The soft gripper completely disregards the size, shape, and mass distribution of the grasping target object.

Fan argued that the horizontal-rotary pulling picking method is considered the optimal strategy for picking apples. However, soft grippers similar to the one designed by Hohime have a bulky structure, making it difficult to perform rotational picking of apples in a cluster-growing state. On the other hand, the more compact soft gripper designed by Wang can achieve this.

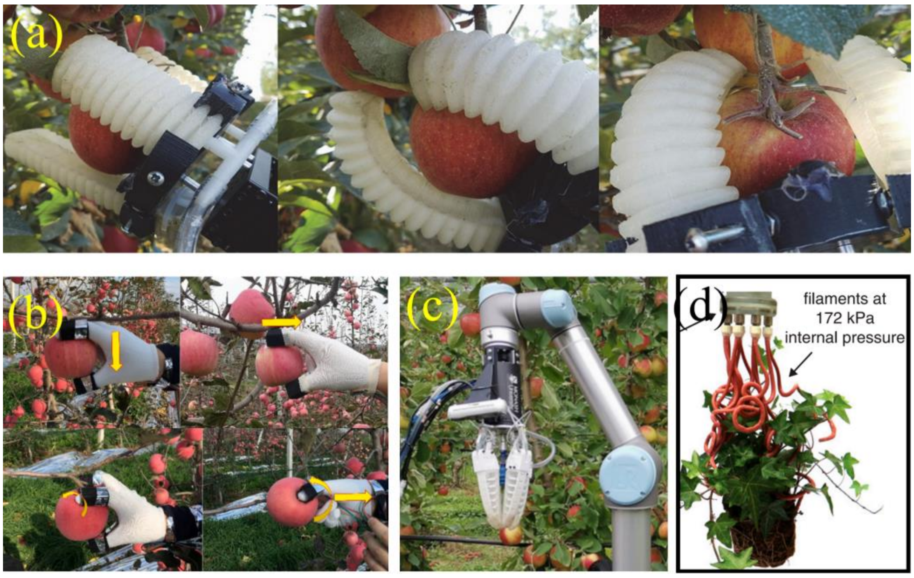

Figure 2. Pneumatic soft gripper with claw structure for use in agricultural harvesting. (**a**) The three-finger pneumatic soft gripper. (**b**) Demonstration of different gripping and picking strategies for apples. (**c**) The soft gripper with gripping and adsorption. (**d**) The soft gripper based on collective mechanics. Figure taken from [12,26–28].

2.1.2. Claw Structure Soft Grippers with Motor Actuation

Motors are typically used for driving and controlling traditional rigid robots and grippers, enabling precise control of the robot's angle, speed and position. When motors are combined with soft mechanical structures, not only do they retain the flexibility of the mechanical structure, but they also significantly improve the robot's responsiveness, control accuracy, and stability. This combination provides reliable hardware support for realizing the complex control algorithms required for the soft contact between the gripper and the fruit in picking operations [29,30].

Chen et al. [31] designed a three-finger motor actuation soft gripper based on the Fin-Ray structure, as shown in Figure 3a. The mechanical model was established through the mapping relationship of grasping force, picking pull force and servo motor torque, which can realize the constant force grasping of apples of different sizes. In apple picking experiments, the picking success rate of this soft gripper was only 80% of that of the rigid gripper, but there was no fruit damage during the picking process. Goulart et al. [32] designed soft grippers with two-finger, four-finger, and six-finger structures, as shown in Figure 3b, and verified the effect of the wrapping area of the soft gripper on the success rate of mango picking. The experiment showed that increasing the number of fingers of the Fin-Ray structure can effectively increase the success rate of mango picking. Xu et al. [33] mathematically modeled the flexible fingers of the Fin-Ray structure and realized the precise control of the flexible fingers by motors. The experimental results show that the average error of force control is less than 3% under the closed-loop control condition without any force sensor. The structure of the soft gripper is shown in Figure 3c.

The soft grippers described above, composed of motors and flexible fingers with a Fin-Ray structure, offer good control accuracy and stability. The main reason is that, within the motor's load range, its response speed and control accuracy are much better than the pressure control used in fluid drive systems. However, motor control also has drawbacks. Since agricultural harvesting is a repetitive and long-duration task, and to minimize the impact of motor size on the dexterity of the soft gripper, the motor is typically selected to operate close to its rated output power. As a result, the motors are often run for extended periods under rated power conditions, which can significantly reduce their service life. Additionally, the compact structural design of soft grippers also impacts the heat dissipation of the motors, thereby affecting their performance.

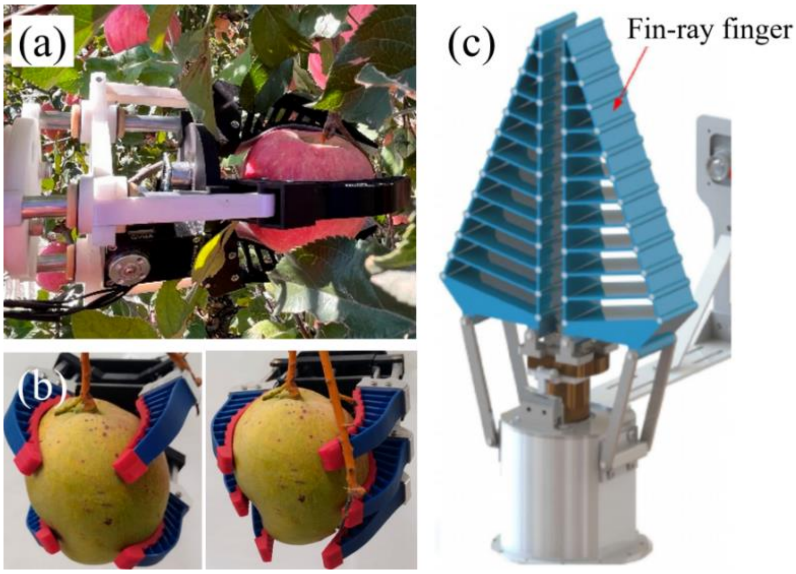

Figure 3. Motor actuation soft grippers with claw structure for use in agricultural harvesting. (**a**) The three-finger Fin-Ray structure soft gripper. (**b**) The four-finger and six-finger Fin-Ray structure soft grippers. (**c**) The two-finger Fin-Ray structure soft gripper. Figure taken from [31–33].

2.1.3. Claw Structure Soft Grippers with Tendon Actuation

Tendon-actuated soft grippers utilize the contraction and tension of tendons to achieve bending, stretching, and twisting movements [34]. When grasping objects with complex contours, tendon-actuated soft grippers generally rely on tendon tension and the compliance of redundant joints to achieve a close fit with the contours of the grasped objects [35]. In addition, the tendon actuation system is characterized by its lightweight and compact structure. Although tendon actuation still relies on motors to drive the system, it effectively extends the control range of the motors and eliminates the need to integrate the motors directly into the soft gripper [36]. Compared with motor actuation, tendon-actuated soft grippers offer better flexibility and load-bearing ratio [37]. Manti et al. [37] combined soft materials, underdriven mechanisms, and bio-inspired design to create a tendon-actuated universal manipulator, as shown in Figure 4a. To ensure adaptability when grasping objects of different shapes, each flexible finger is actuated by a single tendon. Experimental results show that this soft gripper has a strong ability to conform to the contours of grasped objects. Chen et al. [38], inspired by the hunting behavior of spiders, proposed a soft gripper named WebGripper, as shown in Figure 4b. This gripper is characterized by its snake-like winding behavior after grasping an object, providing a wide range of adaptability and grasping stability for various objects. Yu et al. [39] designed an articulated underdriven soft gripper, as shown in Figure 4c. The eight degrees of freedom of the soft gripper are actuated by four tendons. Experimental results show that the picking time for a single citrus fruit is 7.3 s.

The determining factor in the gripping force of a tendon-actuated soft gripper is the tension of the drive tendons. However, prolonged stretching and contraction can cause fatigue failure of the tendons. Therefore, the output force of the tendon decreases as the working hours and frequency increase. Compared with pneumatic artificial muscle actuation and motor actuation, tendon-actuated soft grippers exhibit a lag in response speed. Additionally, the tendon material is affected by the open-air farm environment, which may cause a rapid decline in the material's lifespan due to changes in temperature, humidity, and light, thus reducing the efficiency and stability of the soft gripper in agricultural harvesting operations.

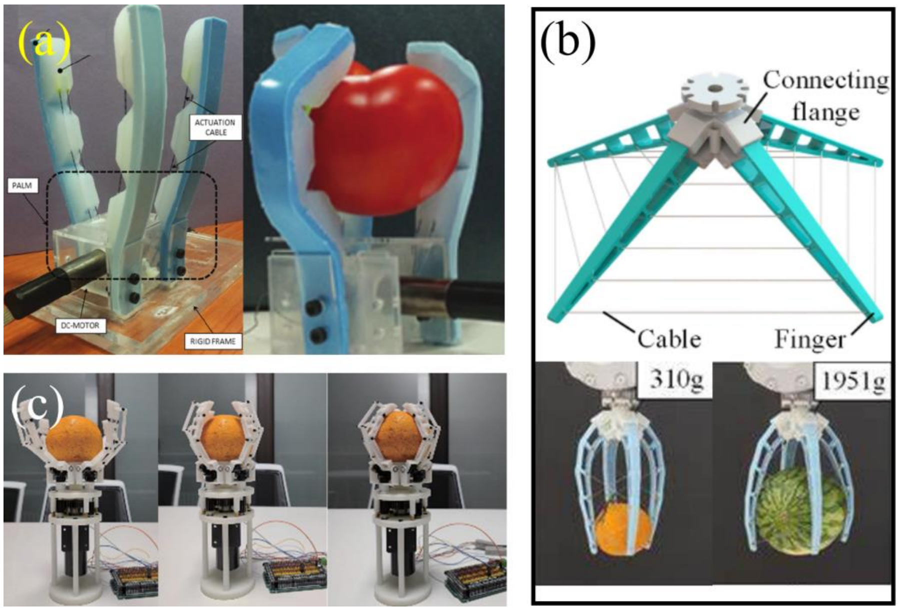

Figure 4. Tendon actuation soft gripper with claw structure for use in agricultural harvesting. (**a**) The three-finger tendon actuation soft gripper. (**b**) The soft gripper made of steel wire and silicone material. (**c**) The soft grippers powered by tendon made of 3D printed materials. Figure taken from [37–39].

2.1.4. Claw Structure Soft Grippers with Smart Material Actuation

Smart material actuation brakes for clawed soft grippers are mainly made of magnetically responsive, thermally sensitive, photosensitive, and dielectric elastomers [40]. These smart materials are characterized by their small size, light weight, and structure-shaping ability, which make the grippers highly flexible and adaptable [41]. In addition, smart materials can be used to design intelligent artificial muscles that exhibit excellent integration and plasticity [42–44].

Magnetic actuation soft grippers can achieve contactless control through magnetic fields, making them suitable for working in closed, narrow, and harsh environments [45]. Generally, the rotation, jumping, movement, and compound motion behaviors of magnetically controlled soft grippers are achieved by varying the magnetic field strength and direction. Additionally, magnetically controlled soft grippers are characterized by fast response times, simple preparation methods, and low manufacturing costs. However, they have several limitations, such as susceptibility to interference from external electromagnetic forces, poor control stability, and insufficient load capacity [46]. Thermal material soft grippers primarily use shape memory alloys or thermal expansion polymers, with folding, twisting, and bending motions achieved by changing the temperature of the material. The control of thermo-sensitive materials generally relies on electrical heating, leading to significant energy loss and susceptibility to interference from ambient temperature changes [47]. Photosensitive materials are typically controlled by irradiating the soft grippers with infrared, ultraviolet, or visible light [48]. Similar to magnetic field control, contactless control can also be realized by adjusting the intensity and direction of the light to control the soft gripper [49]. Dielectric elastomer actuation soft grippers offer advantages such as high deformability, fast response, high energy density, light weight, and dexterity, which make them ideal for multi-degree-of-freedom motion, dynamic tasks, and compact designs [50–53]. However, they require high voltage actuation and have limited load capacity.

Dielectric elastomer actuation soft grippers are more suitable for tasks with low loads and high dynamic response frequencies.

By analyzing the actuation characteristics of smart materials (e.g., magnetic response, thermal sensitivity, photosensitivity, and dielectric elastomers, etc.), it can be concluded that soft grippers based on smart material actuation are not suitable for crop picking operations in natural environments. There are almost no practical application cases in the field of agricultural harvesting.

2.2. Closed Structure Soft Grippers

The actuation methods of enclosed soft grippers mainly include fluid actuation and smart material actuation [54]. Since smart materials are not widely used in agricultural harvesting, this section focuses on the current research status of fluid actuation enclosed soft grippers and their applications in agricultural harvesting. Meanwhile, based on the common grasping characteristics of enclosed soft grippers, they are categorized for discussion into friction grasping and suction grasping.

2.2.1. Friction Grasping Type

Friction grasping soft grippers achieve fixation with the target mainly through static friction. The closed structure of a soft gripper offers higher adaptability to the contour of the grasped target. Compared to the claw structure, the closed structure provides a larger contact area with the object. This results in the closed structure having a significantly higher load capacity than the claw structure. Additionally, the gripping force applied to the surface of the object is more uniform in the closed structure, which is crucial for the non-destructive picking of fruits.

Pedro et al. [55] designed a pneumatic closed soft gripper inspired by the feeding behavior of eels, as shown in Figure 5a. The design features a 3D-printed structure that provides support and stabilization for the silicone closed structure. The outside of the closed structure is covered with a cotton fiber mesh, which serves as a constraint for directional expansion. Experiments were conducted to compare the grip force generated by the soft gripper under the same pressure using fiber meshes with varying levels of looseness and tightness. The experimental results show that the maximum grasping force of this soft gripper is 4.305 N. Sui et al. [56] designed a fluid-filled closed soft gripper inspired by the feeding behavior of blood-worms, as shown in Figure 5b. Its grasping principle is accomplished by driving the WSW to perform an inward–outward flipping motion under the action of the motor screw, thus simulating the swallowing and spitting of food by bloodworms. The experimental results show that its maximum load capacity is 15–20 N. Li et al. [57] took inspiration from the entanglement behavior of plants and animals and designed a closed soft gripper by using traditional pneumatic artificial muscles to simulate the winding behavior, as shown in Figure 5c. The experimental results show that this soft gripper adapts to the grasping of shaped objects and has a maximum load capacity of 105 N. Wang et al. [58] designed a soft gripper by combining two grasping methods, friction and adsorption, as shown in Figure 5d. The grasping principle is to realize the friction grasping of the object inside the flexible structure by inflating and expanding the three air cavities inside the flexible structure. At this time, the surface of the grasped object and the inner wall of the soft structure are closely adhered to each other, and then the vacuum operation inside the soft structure is carried out through the pipe opening at the bottom of the soft structure. As a result of the experiment, the maximum load capacity of the soft gripper can reach 10.85 kg.

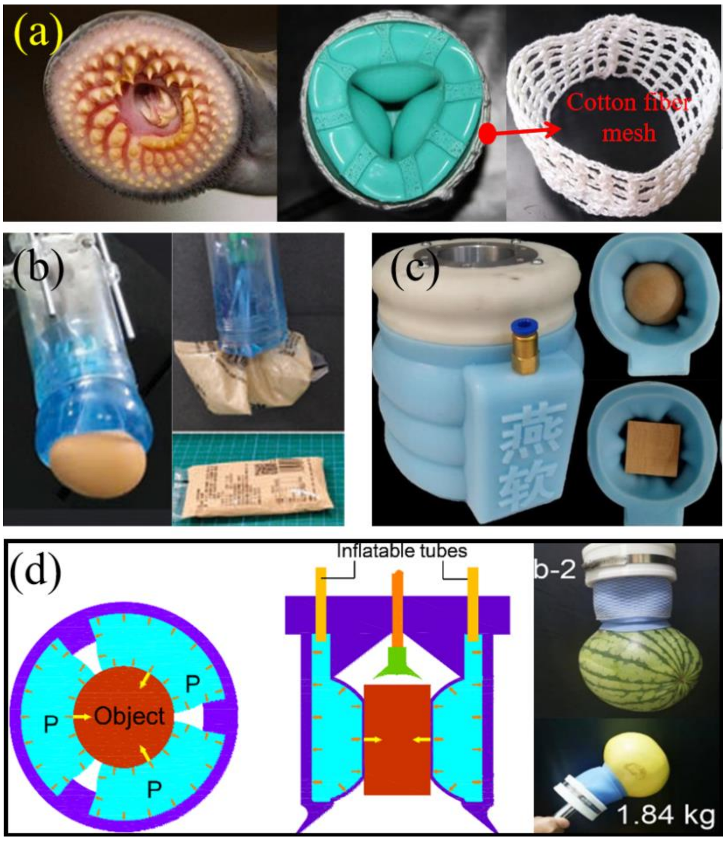

Figure 5. Closed structure friction gripping soft grippers. (**a**) The bionic eel pneumatic soft gripper. (**b**) The soft gripper with friction gripping. (**c**) The bionic winding soft gripper. (**d**) The hybrid gripping soft gripper with suction and friction gripping. Figure taken from [55–58].

From the above literature, it can be seen that, compared to clawed soft grippers, closed soft grippers have a better fit with the gripped object as well as a larger wrapping area, which also gives them a higher load capacity. However, in the field of agricultural harvesting, there are many more cases of claw soft gripper applications than of the closed type. The main reason for this is the poor structural dexterity of closed soft grippers, which leads to a single grasping strategy. In addition, the closed structure has high size requirements and cannot adapt to the size of the object to be grasped by adjusting its own structure. The feature of no deformation ability of closed soft grippers also increases the difficulty of obstacle avoidance in unstructured environments.

2.2.2. Suction Grasping Type

Compared to friction grasping soft grippers, suction grasping soft grippers are smaller and more compact, because they do not need to completely wrap around the object to be grasped in order to exert a gripping force. This feature gives them a significant advantage in space-constrained work scenarios, especially in unstructured agricultural environments, where they can effectively grasp and pick crops that are obscured by leaves or branches. As a result, the suction soft gripper not only inherits the advantages of the enclosed soft gripper's high load capacity, but also has higher dexterity.

Zhang et al. [59] developed a gripper for apple picking, which realizes the fixation with the apple by suction and completes the separation of the fruit from the branch by a twisting-pulling-off motion, as shown in Figure 6a. In order to better fit the contour of the apple, the suction nozzle is made of silicone material, and the maximum suction force is 47 N. The picking experiments show that the picking success rate is 82.4% in the environment of artificial rectification, while in the environment without artificial rectification, the picking success rate decreases to 65.2%, and the average picking time of each fruit is 6 s. To automate the harvesting of the *Agaricus bisporus*, Zhao et al. [60] designed a suction grasping soft gripper incorporating particle obstruction variable stiffness technique, as shown in Figure 6b. The flexible part of the gripper mainly consists of a flexible film and quartz particles. Under the action of suction, the flexible film directly contacts the *Agaricus bisporus* and provides it with protection. Meanwhile, the quartz particles provide additional frictional resistance to the flexible film through the blocking effect, which improves the grasping stability. The experimental results showed that the best grasping stability was achieved when the thickness of the film in the flexible structure was 0.9 mm, the filled quartz particles were 200 mesh, and the maximum loading capacity was up to 35 N. In addition, Jo et al. [61] designed a suction soft gripper that can adjust its shape and surface characteristics in real time to adapt to the contour and surface characteristics of cucumber, as shown in Figure 6c. The experimental results showed that the robot had a picking success rate of 86.2% for cucumbers, while the picking damage rate was only 4.7%.

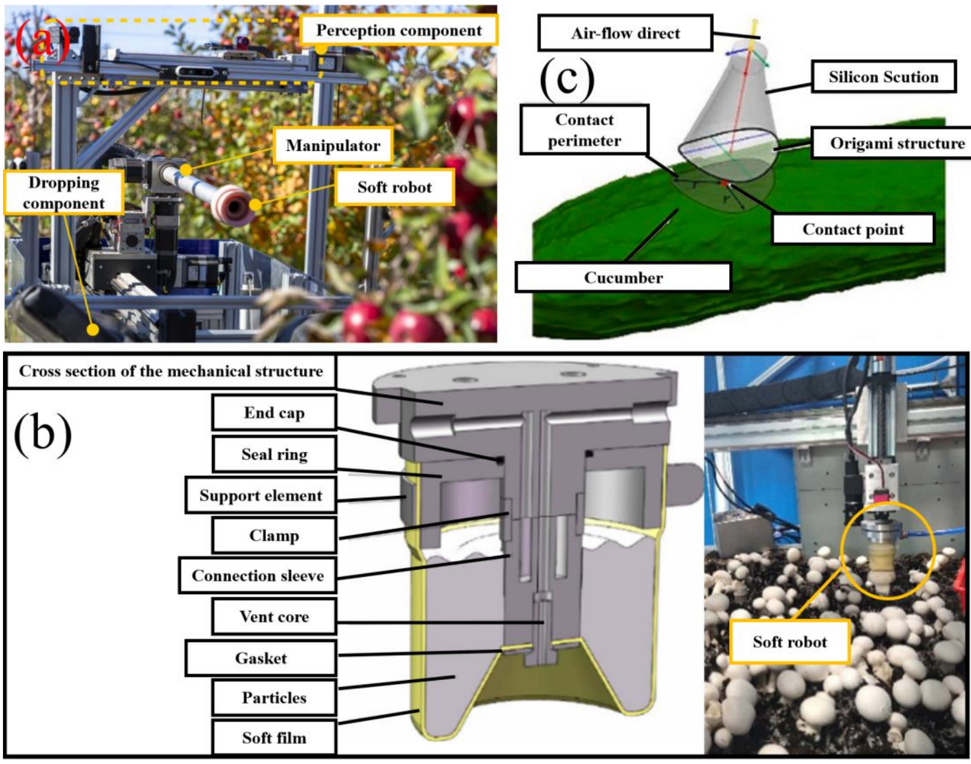

Figure 6. Soft gripper of the suction gripping type. (**a**) The suction gripping structure of soft gripper for apple picking. (**b**) The closed soft gripper with variable stiffness via particle obstruction. (**c**) The suction gripping structure of soft gripper for cucumber picking. Figure taken from [59–61].

Although suction gripping excels in terms of load capacity and dexterity, it places high demands on the crop contact surface during crop harvesting. The suction end must maintain a good seal while in contact with the crop, which poses a greater adaptability challenge. During suction picking of herbaceous crops such as tomatoes and cucumbers, fine leaves and branches can easily be sucked inside the soft structure, which can lead to blockage or damage. In addition, since the wrapping area of the crop by suction grasping is much smaller than that of soft grippers with friction grasping, the picking process is more likely to result in crop damage, which in turn increases the rate of picking damage.

2.3. Summary

Most fruits and vegetables are grown in dense and unstructured environments, which poses a great challenge in realizing their automated picking [62,63]. In such environments, if conventional rigid mechanical grippers are used as a harvesting end-effector, they are prone to collision with non-target objects (e.g., leaves, stems, branches, and other fruits), which leads to frequent sensing and control errors, and may even severely damage the end-effector [64,65]. This not only dramatically increases the maintenance cost of harvesting grippers, but also significantly reduces their operational efficiency. Therefore, in this agricultural environment, soft grippers as an end-effector can effectively avoid damage to precision parts due to collisions. Especially for herbaceous fruits (e.g., tomatoes) and vegetables (e.g., eggplants, cucumbers), the end-effector faces greater challenges in obstacle avoidance due to heavy branch and leaf shading [66,67]. This requires soft grippers to have a compact structure, along with a certain degree of dexterity. For woody fruits (e.g., apples, oranges, mangoes, and pears), soft grippers need to have excellent wrapping performance and stability of gripping force control to minimize mechanical damage during picking [68]. In addition, the soft gripper must also have high load capacity and stiffness, in order to achieve effective separation of the fruit from the trunk [27]. Therefore, the application of soft grippers in agricultural harvesting requires them to have good load capacity and stiffness, a compact structure, a larger crop packaging area, high dexterity, control stability, and sensing capability, as shown in Figure 7.

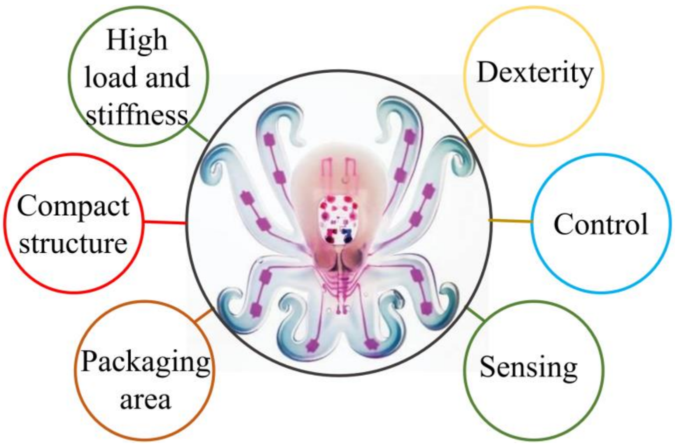

Figure 7. Performance requirements for soft grippers applied to agricultural harvesting.

3. Improvement of Load Performance and Stiffness of Soft Grippers

The main feature of soft grippers that distinguishes them from traditional rigid grippers is their good flexibility, which is the prerequisite for their good environmental adaptability. In order to ensure the flexibility of soft grippers, the Young's modulus of the materials used for the preparation of soft grippers is generally in the range of 10^4–10^9 MPa [69]. However, the soft structure and low stiffness properties of the materials make it difficult to adjust the motion attitude under high loads, which has become one of the major challenges in their transition from laboratory environments to frontline applications [70].

We summarize recent research literature on the load capacity of claw-structured and closed-structured soft grippers, as shown in Figure 8 [71–95]. And show the soft gripper structures with different varying load carrying capacity in Figures 9 and 10. As shown in the figure, the load capacity of closed-structured soft grippers is significantly higher than that of claw-structured soft grippers. In addition, the load capacity of claw-structured soft grippers increases with the number of fingers, demonstrating the characteristic that a larger wrapping area of the soft gripper around the gripped object results in a stronger load capacity. For closed-structured soft grippers, the load capacity of friction grasping is significantly higher than that of suction grasping. This is mainly because suction soft grippers are limited by the surface material and structure of the object being grasped, resulting in relatively lower load capacity.

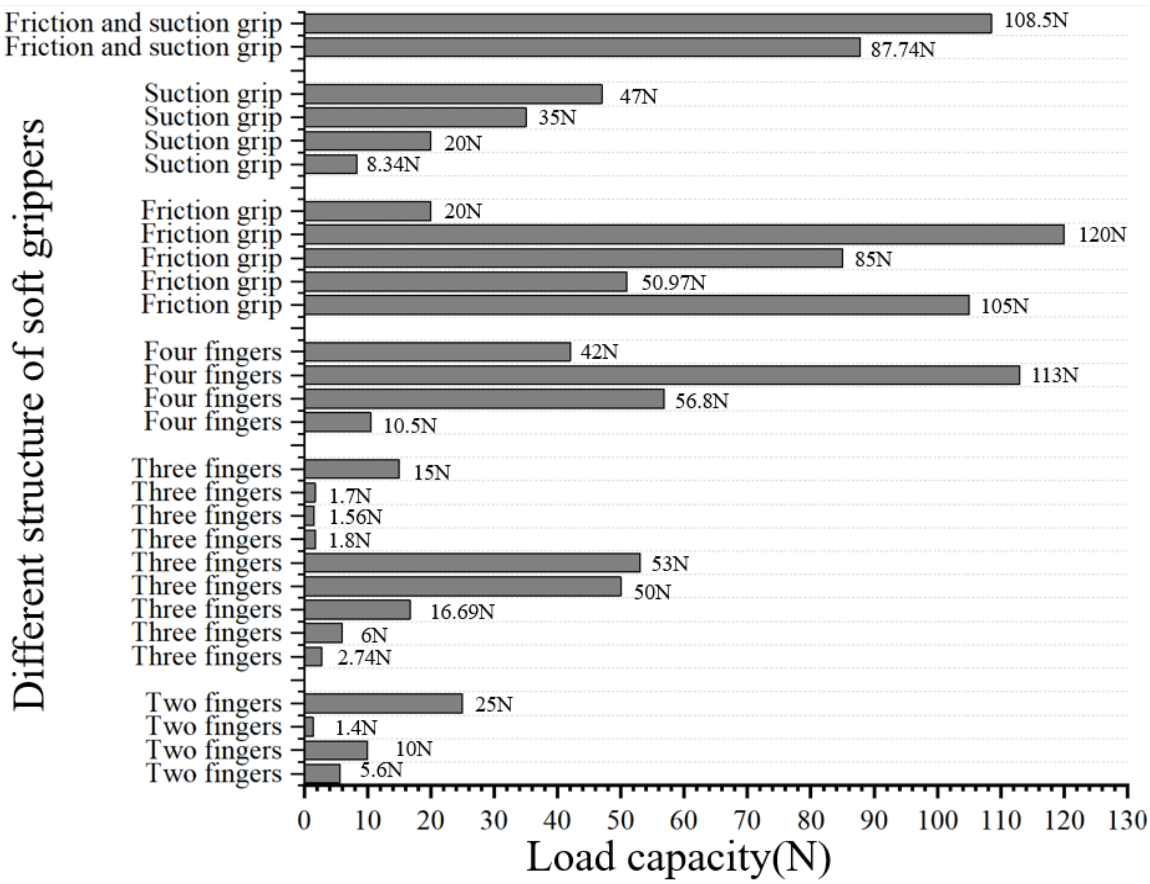

Figure 8. Summary of load capacity of soft grippers with different structural forms.

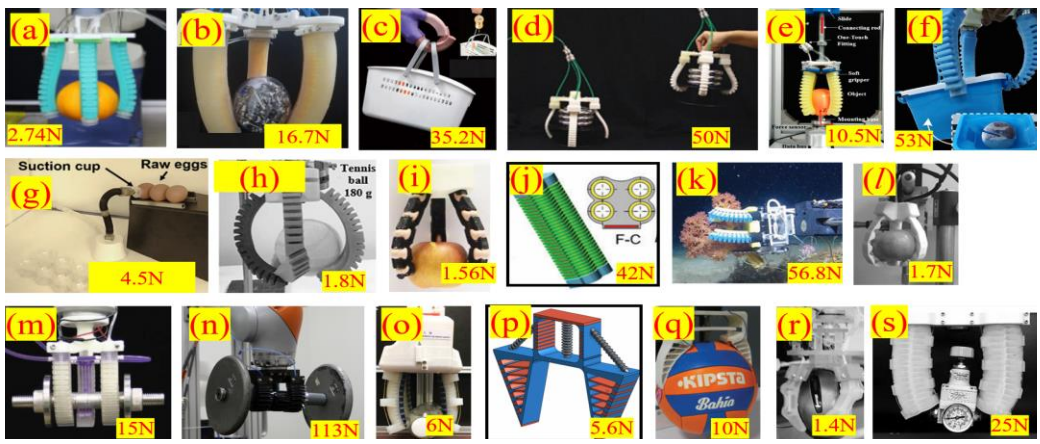

Figure 9. Structural design of clawed soft grippers for agricultural harvesting operations. Figure taken from. (**a**) The pneumatic three-finger soft gripper. (**b**) The pneumatic three-finger soft gripper with improved obstruction variable stiffness. (**c**) The pneumatic five-finger soft gripper. (**d**) The three-finger gripper. (**e**) The four-finger soft gripper. (**f**) The high-load three-finger soft gripper. (**g**) The one-finger soft gripper. (**h**) The pneumatic three-finger soft gripper. (**i**) The three-finger soft gripper.

(**j**) The four-finger soft gripper. (**k**) The pneumatic four-finger soft gripper. (**l**) The tendon-actuated three-finger soft gripper. (**m**) The soft gripper with improved combined material variable stiffness. (**n**) The four-finger soft gripper. (**o**) The three-finger soft gripper. (**p**) The two-finger soft gripper. (**q**) The two-finger soft gripper. (**r**) The pneumatic three-finger soft gripper. (**s**) The two-finger soft gripper with improved antagonistic variable stiffness [74–92].

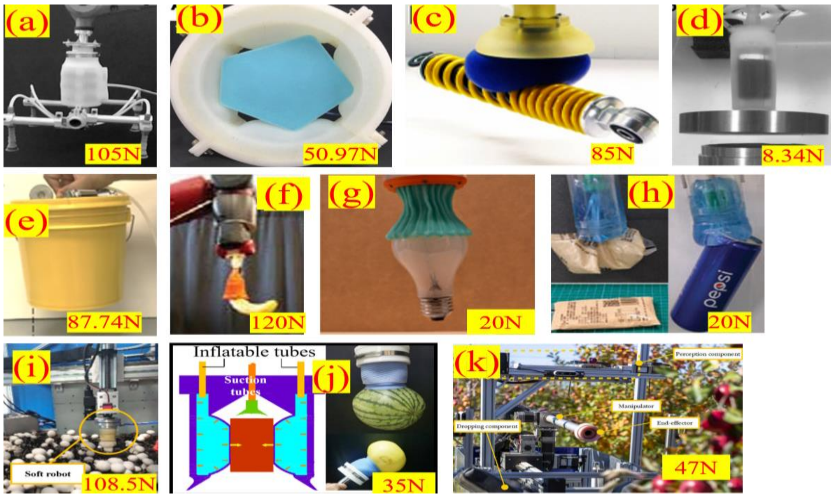

Figure 10. Structural design of closed soft grippers for agricultural harvesting operations. (**a**) The experiment of closed soft gripper gripping shaped object. (**b**) The closed soft gripper with four air chambers control. (**c**) The closed soft gripper with improved obstruction variable stiffness. (**d**) The dielectric elastomer-actuated closed soft gripper. (**e**) The closed soft gripper gripping experiment for a plastic drum. (**f**) The closed soft gripper. (**g**) The closed soft gripper gripping experiment for a light. (**h**) The fluid-obstructed stiffness soft gripper. (**i**) The particle obstruction variable stiffness closed soft gripper. (**j**) The experiments on fruit grasping by a closed soft gripper. (**k**) The closed soft gripper for apple picking. Figure taken from [93–101].

3.1. Classification and Application of Variable Stiffness Methods

In order for soft grippers to meet the requirements of flexibility and high loads, researchers have conducted extensive studies on realizing variable stiffness control [96,97]. Based on the summary of previous techniques, we classify the existing variable stiffness techniques for soft grippers into two categories, active and passive, as shown in Figure 11 [98]. Active variable stiffness techniques, such as electrical, thermal, magnetically induced, and antagonistic variable stiffness, require additional energy interventions, beyond the robot drive energy [92–95]. In contrast, passive variable stiffness techniques, such as obstruction and composite variable stiffness, do not require additional energy stimulation to increase the stiffness of soft grippers [99–105].

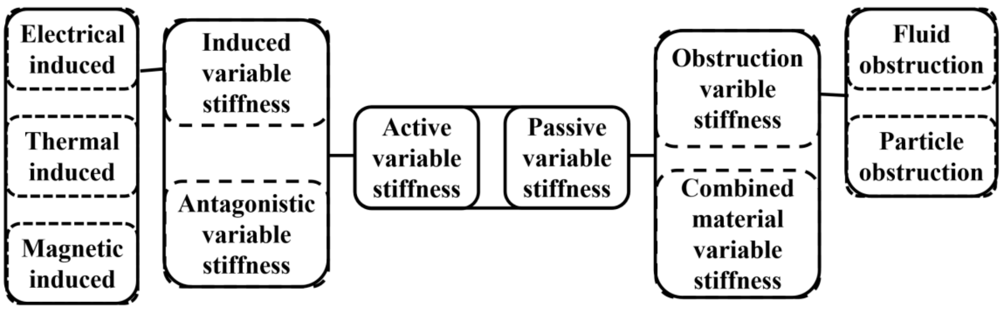

Figure 11. Summary of variable stiffness methods for soft grippers.

Zhang et al. [82] proposed a variable stiffness method for soft grippers with fast response capability and adjustable stiffness. Joule heating circuits and fluid cooling microchannels were attached inside the body of the pneumatic brake by multi-material 3D printing technology. Experimental results showed a 120 times increase in stiffness with a maximum load of 15 N, as shown in Figure 9m. Hoang et al. [106] proposed a method to embed thermal responsive variable stiffness to increase the stiffness of a fluid actuation soft gripper. These thermal responsive materials were attached to the inside of the fingers using a bionic gecko adhesive, as shown in Figure 12a. Experiments have demonstrated that heating these thermally sensitive materials can increase their bending stiffness by up to 26 times their original stiffness. Gaeta et al. [107] proposed a novel magnetically controlled reinforcement method, which controls the stiffness of the soft gripper by increasing the yield stress of the fluid as well as the clamping force between the permanent magnets. The loading of the soft gripper under energized and non-energized conditions is shown in Figure 12b. Jing et al. [108] developed a variable stiffness soft gripper using electrorheological fluid (ER fluid). Experiments showed that when the fluid was not energized and subjected to an external force, it thickened, and the shear force increased. When energized and the external force was removed, the fluid maintained its deformed shape. Upon removal of the voltage, the fluid returned to its original shape, as shown in Figure 12c.

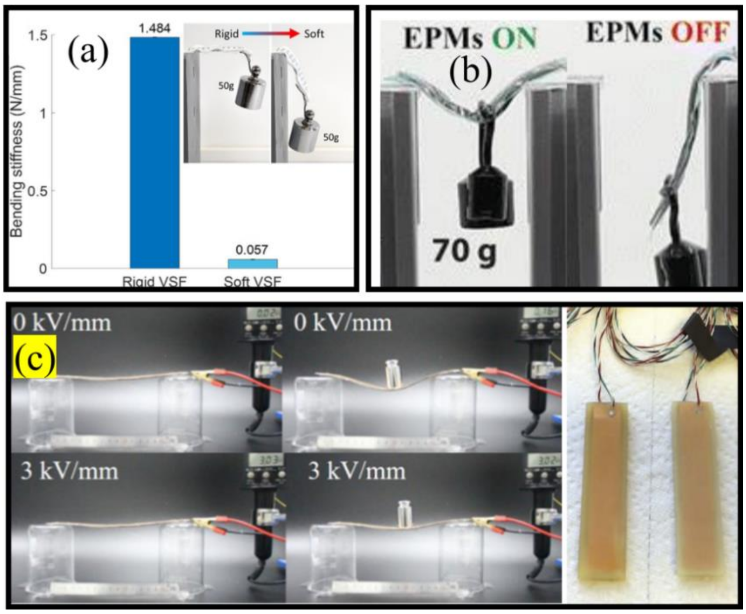

Figure 12. Application of thermal, magnetic, and electrically induced variable stiffness technology. (**a**) Bending stiffness of the soft gripper under cooling and heating conditions. (**b**) EPMs demonstration of the soft gripper load capacity under energized and unenergized conditions. (**c**) Stiffness of the soft gripper filled with ER fluid at different voltages. Figure taken from [106–108].

Liu et al. [79] experimentally determined that the load capacity of the flexible finger is positively correlated with the number of pneumatic chambers of the flexible finger. The driving force of the four-chamber flexible finger is improved by 9.33, 3.5, and 1.5 times compared with that of the single-chamber, two-chamber, and three-chamber versions, respectively, and the four-chamber structure is shown in Figure 9j. Xu et al. [109] designed a soft gripper with real-time variable stiffness capability. It primarily consists of three chambers that antagonize each other to achieve bending control of the soft gripper. Experiments demonstrated that the soft gripper could withstand a load of 0.025–0.138 N/mm, as shown in Figure 13a. Guo et al. [110] placed an elastic tendon inside the pneumatic actuator with a certain preload force, as shown in Figure 13b. When not filled with compressed air, the soft gripper naturally bent under the preload force. After compressed air was introduced, the soft gripper bent in the opposite direction. The experimental results show that the response speed of the soft gripper increased by at least 3.1 times and the stiffness increased by 22 times.

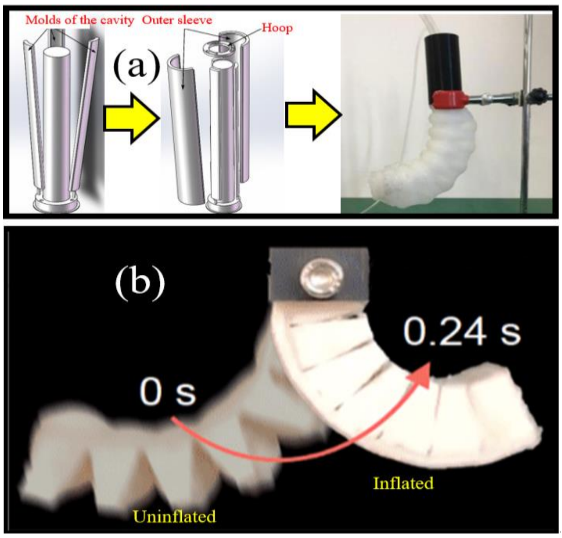

Figure 13. Application of antagonistic variable stiffness technology. (**a**) Triple air cavity antagonist actuation. (**b**) Tendon and air cavity antagonistic actuation. Figure taken from [109,110].

Jiang et al. [71] proposed a variable stiffness soft gripper based on the particle obstruction principle. It is characterized by a dual-cavity structure with particles inside one of the cavities. The soft gripper has only unidirectional bending characteristics. The differential pressure causes the particles inside the chamber to squeeze each other when the air chamber with particles is pumped positively empty, thus significantly increasing the actuator's load capacity. The maximum load capacity of the soft gripper is 16.69 N and the structure is shown in Figure 9b. Shahid et al. [87] designed a soft gripper with adjustable joint stiffness. The finger of the soft gripper is composed of two silicone materials with different stiffness levels and the joint stiffness is adjusted using pneumatic pressure. The motion of the soft gripper's finger is actuated by tendons, as illustrated in Figure 14a. Experimental results show that the maximum load capacity of the soft gripper is 1.4 N. The overall structure of the soft gripper is depicted in Figure 9r. Han et al. [111] proposed a novel particle obstruction variable stiffness method. This method adjusts stiffness by controlling the quantity of particles filled within the soft structure. As the number of particles in the inner cavity of the soft gripper increases, its bending stiffness also increases, as shown in Figure 14b.

To address the issue of insufficient load capacity in pneumatic actuators caused by limitations in material properties and manufacturing processes, Li et al. [75] proposed a method to enhance the load capacity of pneumatic actuators. First, the soft pneumatic actuators were designed in two parts: an actuation core consisting of a fiber-reinforced airbag and an elastic support made of a soft material, which were fabricated separately. Second, the two parts were combined using assembly and recasting techniques to produce the finished actuator, as shown in Figure 15. Experimental results indicate that this method significantly improves the stiffness and load capacity of the soft gripper, enabling it to lift objects weighing up to 53 N, as shown in Figure 9f.

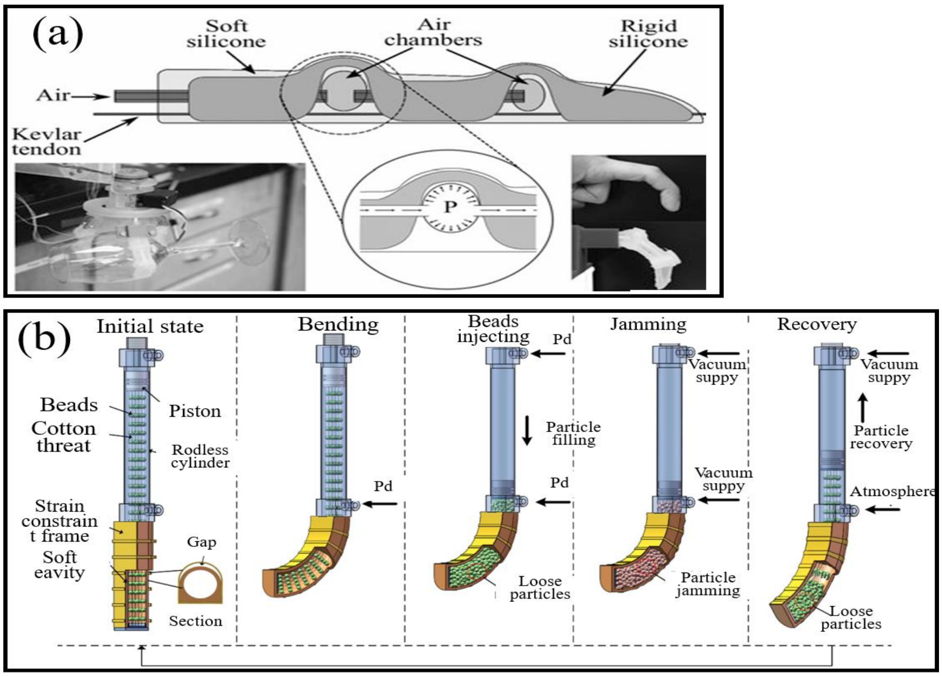

Figure 14. Application of obstruction variable stiffness in soft grippers. (**a**) Structural diagram of the soft gripper with variable stiffness of fluid obstructed. (**b**) Real-time control method for variable stiffness of particle obstruction. Figure taken from [87,111].

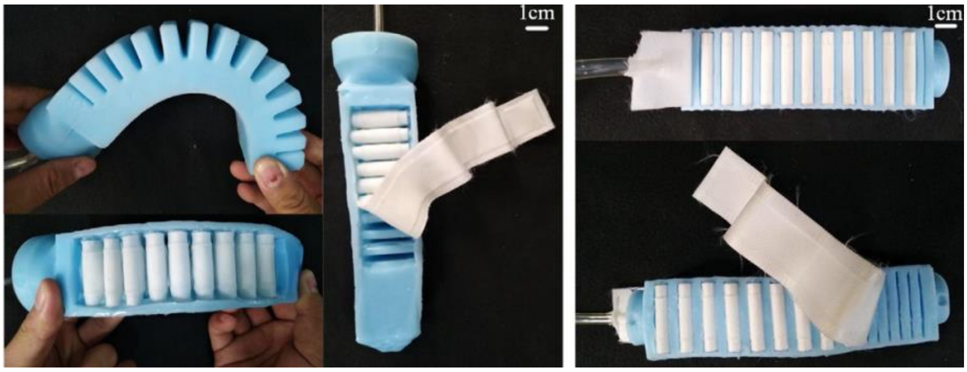

Figure 15. Application of combined material variable stiffness in the soft gripper. Figure taken from [75].

3.2. Summary

We summarize the application of variable stiffness technology in enhancing the load capacity of soft grippers, starting from its effect on load capacity and stiffness, dexterity, degree of integration, responsiveness, and energy consumption. We also summarize the advantages and disadvantages of its application in the field of agricultural harvesting, as shown in Figure 16. This figure summarizes the characteristics of various variable stiffness methods, as follows: thermal-induced variable stiffness methods are summarized in the literature [82,106,112–116]; magnetic-induced methods are summarized in the literature [107,117–124]; electrical-induced methods are summarized in the literature [108,125–127]; antagonistic variable stiffness methods are summarized in the literature [79,102,109,110,128–130]; fluid obstruction-based methods are summarized in the literature [71,103,111,131–133]; particle obstruction-based methods are summarized in the literature [87,105,134]; and combined material variable stiffness methods are summarized in the literature [75,104].

Classification			Performance enhancement for soft robots				
			Load and stiffness	Dexterity	Degree of intergration	responsiveness	energy consumption
Active variable stiffness	Induced variable stiffness	Thermal induced	×	○	○	×	×
		Magnetic induced	×	○	○	○	×
		Electrical induced	×	×	×	○	×
	Antagonistic variable stiffness		○	×	×	○	×
Passive variable stiffness	Obstruction varible stiffness	Fluid obstruction	○	×	×	○	○
		Particle obstruction	○	×	×	○	○
	Combined material variable stiffness		○	×	○	○	○

"○" in the table indicates that the type of variable stiffness is conducive to the performance improvement of the item.
"×" in the table indicates that the type of variable stiffness is not conducive to the performance improvement of the item.

Figure 16. Summary of advantages and disadvantages of different soft gripper variable stiffness techniques.

According to the above literature summary, the responsiveness is slow and usually takes more than tens of seconds when the thermally induced variable stiffness technique is used to improve the stiffness of soft grippers. Therefore, the method of thermally induced variable stiffness is not suitable for tasks such as agricultural picking, which require efficient operation. In addition, the natural environment may adversely affect the performance of variable stiffness materials controlled by thermal mechanisms.

The materials used in magnetically induced variable stiffness technology mainly include magnetorheological elastomers (MREs) and magnetorheological fluids (MRFs). The responsiveness of MREs and MRFs is on the order of milliseconds, compared to thermally induced variable stiffness materials. However, the magnetically induced variable stiffness method requires a strong magnetic field and precise control of its size and direction, which leads to a bulky magnetic field generator, thereby affecting the dexterity and integration of soft grippers.

Electrically induced variable stiffness techniques have much faster responsiveness, typically in the order of micrometers, than magnetically induced variable stiffness techniques. The electrical actuation materials, such as electrorheological fluids (ERFs) and dielectric elastomers (DEs), are the key materials for electrically induced variable stiffness. However, the effectiveness of electrically induced variable stiffness techniques in enhancing the loading capacity of soft grippers is limited, due to the low loading capacity of ERFs and DEs. This limitation is similar to that of magnetically induced and thermally induced variable stiffness techniques.

The biggest advantage of antagonistic variable stiffness technology is that it can significantly increase the load capacity and response speed of soft grippers. However, multiple actuators are usually required, which leads to a reduction in the integration level of the soft grippers and hence their dexterity. This makes it difficult for antagonistic stiffness techniques to meet the demands for small size and high dexterity of soft grippers in complex agricultural environments.

Obstructive variable stiffness techniques can also be effective in increasing the load capacity of soft grippers. Similar to the antagonistic stiffness technique, the obstructive stiffness technique may reduce the dexterity and degree of integration of the soft gripper. However, unlike antagonistic variable stiffness techniques, obstructive variable stiffness techniques do not require additional energy loss.

The method of combined material variable stiffness involves attaching a high Young's modulus material to the critical stress points of a low Young's modulus soft gripper, thereby increasing the overall loading capacity of the soft gripper. This method offers a high degree of integration with soft grippers, as it only reinforces the structure, does not affect the responsiveness, and does not require additional actuators. However, the dexterity of soft grippers is reduced, due to the limitations of high Young's modulus materials. In contrast, the combined material variable stiffness method is more suitable for enhancing the performance of soft grippers in agricultural harvesting environments.

4. Conclusions

This review summarizes the four main actuation methods—fluid actuation, smart material actuation, motor actuation, and tendon actuation—and analyzes the application of soft grippers with two structural types—claw structure and closed structure—in the field of agricultural harvesting. Through literature compilation and analysis, we explore the effects of combining different actuation methods and structure types on the performance of soft grippers. Finally, we summarize the six major performance requirements for soft grippers in agricultural harvesting: high load and stiffness, compact structure, wrapping area, dexterity, control accuracy, and sensing capability.

The lack of load capacity and stiffness is one of the important issues that limits the wide application of soft grippers in agricultural harvesting. To address this problem, this review summarizes the variable stiffness methods for soft grippers and classifies different variable stiffness techniques. We analyze the effects of variable stiffness techniques on the load capacity, stiffness, dexterity, degree of integration, responsiveness, and energy consumption of soft grippers. We discuss the advantages and disadvantages of these variable stiffness methods in enhancing the load capacity of soft grippers used in agricultural harvesting.

Ultimately, this paper concludes that combined material variable stiffness technology, along with motor actuation claw structures in soft grippers, is more suitable for agricultural harvesting operations in unstructured environments.

Author Contributions: Conceptualization, D.Z. and H.Y. (Hualin Yang); methodology, W.Z.; software, H.Y. (Haibing Yang); validation, W.Z.; formal analysis, W.Z.; investigation, H.Y. (Haibing Yang); resources, D.Z.; data curation, W.Z.; writing—original draft preparation, W.Z. and H.Y. (Haibing Yang); writing—review and editing, D.Z. and H.Y. (Hualin Yang); visualization, D.Z.; supervision, D.Z. and H.Y. (Hualin Yang); project administration, D.Z.; funding acquisition, D.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Smart Farm Design and Development Project (ZXKY20230528).

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Yasa, O.; Toshimitsu, Y.; Michelis, M.Y.; Jones, L.S.; Filippi, M.; Buchner, T.; Katzschmann, R.K. An overview of soft robotics. *Annu. Rev. Control. Robot. Auton. Syst.* **2023**, *6*, 1–29. [CrossRef]
2. Zhang, Y.; Li, P.; Quan, J.; Li, L.; Zhang, G.; Zhou, D. Progress, challenges, and prospects of soft *robotics* for space applications. *Adv. Intell. Syst.* **2023**, *5*, 2200071. [CrossRef]
3. Li, J.; Cao, J.; Lu, B.; Gu, G. 3D-printed PEDOT: PSS for soft robotics. *Nat. Rev. Mater.* **2023**, *8*, 604–622. [CrossRef]
4. Guo, Y.; Qin, Q.; Han, Z.; Plamthottam, R.; Possinger, M.; Pei, Q. Dielectric elastomer artificial muscle materials advancement and soft robotic applications. *SmartMat* **2023**, *4*, e1203. [CrossRef]
5. Chi, Y.; Zhao, Y.; Hong, Y.; Li, Y.; Yin, J. A perspective on miniature soft robotics: Actuation, fabrication, control, and applications. *Adv. Intell. Syst.* **2024**, *6*, 2300063. [CrossRef]
6. Yang, X.; Lan, L.; Pan, X.; Di, Q.; Liu, X.; Li, L. Bioinspired soft robots based on organic polymer-crystal hybrid materials with response to temperature and humidity. *Nat. Commun.* **2023**, *14*, 2287. [CrossRef] [PubMed]

7. Stella, F.; Hughes, J. The science of soft robot design: A review of motivations, methods and enabling technologies. *Front. Robot. AI* **2023**, *9*, 1059026. [CrossRef]
8. Trivedi, D.; Rahn, C.D.; Kier, W.M.; Walker, I.D. Soft robotics: Biological inspiration, state of the art, and future research. *Appl. Bionics Biomech.* **2008**, *5*, 99–117. [CrossRef]
9. Lee, C.; Kim, M.; Kim, Y.J.; Hong, N.; Ryu, S.; Kim, H.J.; Kim, S. Soft robot review. *Int. J. Control. Autom. Syst.* **2017**, *15*, 3–15. [CrossRef]
10. Elfferich, J.F.; Dodou, D.; Della Santina, C. Soft robotic grippers for crop handling or harvesting: A review. *IEEE Access* **2022**, *10*, 75428–75443. [CrossRef]
11. Navas, E.; Fernández, R.; Sepúlveda, D.; Armada, M.; Gonzalez-de-Santos, P. Soft grippers for automatic crop harvesting: A. review. *Sensors* **2021**, *21*, 2689. [CrossRef] [PubMed]
12. Wang, X.; Kang, H.; Zhou, H.; Au, W.; Wang, M.Y.; Chen, C. Development and evaluation of a robust soft robotic gripper for apple harvesting. *Comput. Electron. Agric.* **2023**, *204*, 107552. [CrossRef]
13. Roshanfar, M.; Dargahi, J.; Hooshiar, A. Cosserat rod-based dynamic modeling of a hybrid-actuated soft robot for robot-assisted cardiac ablation. *Actuators* **2023**, *13*, 8. [CrossRef]
14. Xu, S.; Zhang, S.; Lei, R.; Liu, Y.; Bu, W.; Wei, X.; Zhang, Z. Fluid-driven and smart material-driven research for soft body robots. *Prog. Nat. Sci. Mater. Int.* **2023**, *33*, 371–385. [CrossRef]
15. Bu, K.; Gong, X.; Yu, C.; Xie, F. Biomimetic aquatic robots based on fluid-driven actuators: A review. *J. Mar. Sci. Eng.* **2022**, *10*, 735. [CrossRef]
16. Chen, S.; Wang, H.Z.; Liu, T.Y.; Liu, J. Liquid metal smart materials toward soft robotics. *Adv. Intell. Syst.* **2023**, *5*, 2200375. [CrossRef]
17. Hines, L.; Petersen, K.; Lum, G.Z.; Sitti, M. Soft actuators for small-scale robotics. *Adv. Mater.* **2017**, *29*, 1603483. [CrossRef]
18. Liu, C.H.; Chung, F.M.; Chen, Y.; Chiu, C.H.; Chen, T.L. Optimal design of a motor-driven three-finger soft robotics gripper. *IEEE/ASME Trans. Mechatron.* **2020**, *25*, 1830–1840. [CrossRef]
19. Konda, R.; Bombara, D.; Chow, E.; Zhang, J. Kinematic modeling and open-loop control of a twisted string actuator-driven soft robotics manipulator. *J. Mech. Robot.* **2024**, *16*, 041007. [CrossRef]
20. Zhu, J.Q.; Pu, M.H.; Chen, H.; Xu, Y.; Ding, H.; Wu, Z. Pneumatic and tendon actuation coupled muti-mode actuators for soft robotis with broad force and speed range. *Sci. China Technol. Sci.* **2022**, *65*, 2156–2169. [CrossRef]
21. Bilodeau, R.A.; White, E.L.; Kramer, R.K. Monolithic fabrication of sensors and actuators in a soft robotic gripper. In Proceedings of the 2015 IEEE/RSJ International Conference on Intelligent grippers and Systems (IROS), Hamburg, Germany, 28 September–2 October 2015; pp. 2324–2329.
22. Ham, J.; Han, A.K.; Cutkosky, M.R.; Bao, Z. UV-laser-machined stretchable multi-modal sensor network for soft robot interaction. *NPY Flex. Electron.* **2022**, *6*, 94. [CrossRef]
23. Li, W.; Wang, Z.; Mai, R.; Ren, P.; Zhang, Q.; Zhou, Y.; Xu, N.; Zhuang, J.F.; Xin, B.; Gao, L.; et al. Modular design automation of the morphologies, controllers, and vision systems for intelligent robots: A survey. *Vis. Intell.* **2023**, *1*, 2. [CrossRef]
24. Su, H.; Hou, X.; Zhang, X.; Qi, W.; Cai, S.; Xiong, X.; Guo, J. Pneumatic soft robots: Challenges and benefits. *Actuators* **2022**, *11*, 92. [CrossRef]
25. An, N.; Li, M.; Zhou, J. Modeling and understanding locomotion of pneumatic soft robots. *Soft Mater.* **2018**, *16*, 151–159. [CrossRef]
26. Hohimer, C.J.; Wang, H.; Bhusal, S.; Miller, J.; Mo, C.; Karkee, M. Design and field evaluation of a robotic apple harvesting system with a 3D-printed soft-robotic end-effector. *Trans. ASABE* **2019**, *62*, 405–414. [CrossRef]
27. Fan, P.; Yan, B.; Wang, M.; Lei, X.; Liu, Z.; Yang, F. Three-finger grasp planning and experimental analysis of picking patterns for robotic apple harvesting. *Comput. Electron. Agric.* **2021**, *188*, 106353. [CrossRef]
28. Becker, K.; Teeple, C.; Charles, N.; Jung, Y.; Baum, D.; Weaver, J.C.; Mahadevan, L.; Wood, R. Active entanglement enables stochastic, topological grasping. *Proc. Natl. Acad. Sci. USA* **2022**, *119*, e2209819119. [CrossRef] [PubMed]
29. Liu, S.Q.; Adelson, E.H. Gelsight fin ray: Incorporating tactile sensing into a soft compliant robotic gripper. In Proceedings of the 2022 IEEE 5th International Conference on Soft Robotics (RoboSoft), Edinburgh, UK, 4–8 April 2022; pp. 925–931.
30. Jumet, B.; Bell, M.D.; Sanchez, V.; Preston, D.J. A data-driven review of soft robotics. *Adv. Intell. Syst.* **2022**, *4*, 2100163. [CrossRef]
31. Chen, K.; Li, T.; Yan, T.; Xie, F.; Feng, Q.; Zhu, Q.; Zhao, C. A soft gripper design for apple harvesting with force feedback and fruit slip detection. *Agriculture* **2022**, *12*, 1802. [CrossRef]
32. Goulart, R.; Jarvis, D.; Walsh, K.B. Evaluation of end effectors for robotic harvesting of mango fruit. *Sustainability* **2023**, *15*, 6769. [CrossRef]
33. Xu, W.; Zhang, H.; Yuan, H.; Liang, B. A compliant adaptive gripper and its intrinsic force sensing method. *IEEE Trans. Robot.* **2021**, *37*, 1584–1603. [CrossRef]
34. Lai, J.; Lu, B.; Zhao, Q.; Chu, H.K. Constrained motion planning of a cable-driven soft robot with compressible curvature modeling. *IEEE Robot. Autom. Lett.* **2022**, *7*, 4813–4820. [CrossRef]

35. Wei, F.; Luo, K.; Zhang, Y.; Jiang, J. Structural Design and Kinematic Analysis of Cable-Driven soft robot. *Actuators* **2024**, *13*, 497. [CrossRef]
36. Li, R.; Chen, F.; Yu, W.; Igarash, T.; Shu, X.; Xie, L. A novel cable-driven soft gripper for surgery. *J. Shanghai Jiaotong Univ.* **2024**, *29*, 60–72. [CrossRef]
37. Manti, M.; Hassan, T.; Passetti, G.; D'Elia, N.; Laschi, C.; Cianchetti, M. A bioinspired soft robotic gripper for adaptable and effective grasping. *Soft Robot.* **2015**, *2*, 107–116. [CrossRef]
38. Chen, X.; Yao, J.; Zhang, S.; Zhu, K.; Kong, S.; Qi, S.; Zhang, X. WebGripper: Bioinspired cobweb soft gripper for adaptable and stable grasping. *IEEE Trans. Robot.* **2023**, *39*, 3059–3071. [CrossRef]
39. Yu, L.; Yu, G.; Wu, H.; Sun, F.; Qian, M. Design and experiment of the end-effector with underactuated articulars for citrus picking. *Trans. Chin. Soc. Agric. Eng.* **2023**, *39*, 29–38.
40. Hao, Y.; Zhang, S.; Fang, B.; Sun, F.; Liu, H.; Li, H. A review of smart materials for the boost of soft actuators, soft sensors, and robotics applications. *Chin. J. Mech. Eng.* **2022**, *35*, 37. [CrossRef]
41. Liu, K.; Chen, W.; Yang, W.; Jiao, Z.; Yu, Y. Review of the research progress in soft robots. *Appl. Sci.* **2022**, *13*, 120. [CrossRef]
42. Brochu, P.; Pei, Q. Advances in dielectric elastomers for actuators and artificial muscles. *Macromol. Rapid Commun.* **2010**, *31*, 10–36. [CrossRef]
43. Anderson, I.A.; Gisby, T.A.; McKay, T.G.; O'Brien, B.M.; Calius, E.P. Multi-functional dielectric elastomer artificial muscles for soft and smart machines. *J. Appl. Phys.* **2012**, *112*, 041101. [CrossRef]
44. Qiu, Y.; Zhang, E.; Plamthottam, R.; Pei, Q. Dielectric elastomer artificial muscle: Materials innovations and device explorations. *Acc. Chem. Res.* **2019**, *52*, 316–325. [CrossRef] [PubMed]
45. Chen, J.; Jin, D.; Wang, Q.; Ma, X. Programming ferromagnetic soft materials for miniature soft robots: Design, fabrication, and applications. *J. Mater. Sci. Technol.* **2025**, *219*, 271–287. [CrossRef]
46. Zhang, J.; Diller, E. Untethered miniature soft robots: Modeling and design of a millimeter-scale swimming magnetic sheet. *Soft Robot.* **2018**, *5*, 761–776. [CrossRef] [PubMed]
47. Lahondes, Q.; Miyashita, S. Temperature Driven Soft Reversible Self-folding Origami String. In Proceedings of the 2022 IEEE 5th International Conference on Soft Robotics (RoboSoft), Edinburgh, UK, 4–8 April 2022; pp. 589–594.
48. Han, L.; Si, J.; Zhu, B.; Wang, R.; Wu, C.; Guo, M. A multidirectional locomotion light-driven soft crawling robot. *Adv. Funct. Mater.* **2023**, *33*, 2305046. [CrossRef]
49. Wang, Z.; Shi, D.; Wang, X.; Chen, Y.; Yuan, Z.; Li, Y.; Ge, Z.; Yang, W. A multifunctional light-driven swimming soft robot for various application scenarios. *Int. J. Mol. Sci.* **2022**, *23*, 9609. [CrossRef]
50. Chen, Y.; Zhao, H.; Mao, J.; Chirarattananon, P.; Helbling, E.F.; Hyun, N.P.; Clarke, D.R.; Wood, R.J. Controlled flight of a microrobot powered by soft artificial muscles. *Nature* **2019**, *575*, 324–329. [CrossRef] [PubMed]
51. Duduta, M.; Hajiesmaili, E.; Zhao, H.; Wood, R.J.; Clarke, D.R. Realizing the potential of dielectric elastomer artificial muscles. *Proc. Natl. Acad. Sci. USA* **2019**, *116*, 2476–2481. [CrossRef]
52. Kornbluh, R.D.; Pelrine, R.; Pei, Q.; Heydt, R.; Stanford, S.; Oh, S.; Eckerle, J. Electroelastomers: Applications of dielectric elastomer transducers for actuation, generation, and smart structures. In *Smart Structures and Materials 2002: Industrial and Commercial Applications of Smart Structures Technologies*; SPIE: Bellingham, WA, USA, 2002; Volume 4698, pp. 254–270.
53. Guo, Y.; Liu, L.; Liu, Y.; Leng, J. Review of dielectric elastomer actuators and their applications in soft robots. *Adv. Intell. Syst.* **2021**, *3*, 2000282. [CrossRef]
54. Ankit; Tiwari, N.; Ho, F.; Krisnadi, F.; Kulkarni, M.R.; Nguyen, L.L.; Koh, S.J.A.; Mathews, N. High-k, ultrastretchable self-enclosed ionic liquid-elastomer composites for soft robotics and flexible electronics. *ACS Appl. Mater. Interfaces* **2020**, *12*, 37561–37570. [CrossRef] [PubMed]
55. Pedro, P.; Ananda, C.; Rafael, P.B.; Carlos, A.R.; Alexandre, B.C. Closed structure soft robotic gripper. In Proceedings of the 2018 IEEE International Conference on Soft Robotics (RoboSoft), Livorno, Italy, 24–28 April 2018; pp. 66–70.
56. Sui, D.; Zhu, Y.; Zhao, S.; Wang, T.; Agrawal, S.K.; Zhang, H.; Zhao, J. A bioinspired soft swallowing gripper for universal adaptable grasping. *Soft Robot.* **2022**, *9*, 36–56. [CrossRef] [PubMed]
57. Li, H. Untethered High-Load Soft Grasping Robots Based on Bioinspired Enclosed Grasping Mechanism. Ph.D. Thesis, Yanshan University, Qinhuangdao, China, 2021.
58. Wang, D.; Wu, X.; Zhang, J.; Du, Y. A pneumatic novel combined soft robotic gripper with high load capacity and large grasping range. *Actuators* **2021**, *11*, 3. [CrossRef]
59. Zhang, K.; Lammers, K.; Chu, P.; Li, Z.; Lu, R. An automated apple harvesting robot—From system design to field evaluation. *J. Field Robot.* **2024**, *41*, 2384–2400. [CrossRef]
60. Zhao, K.; Li, H.; Ji, J.; Li, Q.; Li, M.; He, Y.; Li, J.; Xing, S. Pressure-stabilized flexible end-effector for selective picking of *Agaricus bisporus*. *Agriculture* **2023**, *13*, 2256. [CrossRef]
61. Jo, Y.; Park, Y.; Son, H.I. A suction cup-based soft robotic gripper for cucumber harvesting: Design and validation. *Biosyst. Eng.* **2024**, *238*, 143–156. [CrossRef]

62. Wang, Z.; Or, K.; Hirai, S. A dual-mode soft gripper for food packaging. *Robot. Auton. Syst.* **2020**, *125*, 103427. [CrossRef]
63. Wang, Z.; Xun, Y.; Wang, Y.; Qinghua, Y. Review of smart robots for fruit and vegetable picking in agriculture. *Int. J. Agric. Biol. Eng.* **2022**, *15*, 33–54.
64. Blanes, C.; Ortiz, C.; Mellado, M.; Beltrán, P. Assessment of eggplant firmness with accelerometers on a pneumatic robot gripper. *Comput. Electron. Agric.* **2015**, *113*, 44–50. [CrossRef]
65. Cao, X.; Zou, X.; Jia, C.; Chen, M.; Zeng, Z. RRT-based path planning for an intelligent litchi-picking manipulator. *Comput. Electron. Agric.* **2019**, *156*, 105–118. [CrossRef]
66. Hou, Z.; Li, Z.; Fadiji, T.; Fu, J. Soft grasping mechanism of human fingers for tomato-picking bionic robots. *Comput. Electron. Agric.* **2021**, *182*, 106010. [CrossRef]
67. Kultongkham, A.; Kumnon, S.; Thintawornkul, T.; Chanthasopeephan, T. The design of a force feedback soft gripper for tomato harvesting. *J. Agric. Eng.* **2021**, *52*, 1090. [CrossRef]
68. Ji, W.; Zhang, J.; Xu, B.; Tang, C.; Zhao, D. Grasping mode analysis and adaptive impedance control for apple harvesting robotic grippers. *Comput. Electron. Agric.* **2021**, *186*, 106210. [CrossRef]
69. Cianchetti, M.; Laschi, C.; Menciassi, A.; Dario, P. Biomedical applications of soft robotics. *Nat. Rev. Mater.* **2018**, *3*, 143–153. [CrossRef]
70. Wang, W.; Yu, C.Y.; Abrego Serrano, P.A.; Ahn, S.H. Shape memory alloy-based soft finger with changeable bending length using targeted variable stiffness. *Soft Robot.* **2020**, *7*, 283–291. [CrossRef]
71. Jiang, P.; Yang, Y.; Chen, M.Z.Q.; Chen, Y. A variable stiffness gripper based on differential drive particle jamming. *Bioinspiration Biomim.* **2019**, *14*, 036009. [CrossRef] [PubMed]
72. Jiang, Y.; Chen, D.; Liu, C.; Li, J. Chain-like granular jamming: A novel stiffness-programmable mechanism for soft robotics. *Soft Robot.* **2019**, *6*, 118–132. [CrossRef] [PubMed]
73. Yap, H.K.; Ng, H.Y.; Yeow, C.H. High-force soft printable pneumatics for soft robotic applications. *Soft Robot.* **2016**, *3*, 144–158. [CrossRef]
74. Hao, Y.; Gong, Z.; Xie, Z.; Guan, S.; Yang, X.; Ren, Z.; Wang, T.; Wen, L. Universal soft pneumatic robotic gripper with variable effective length. In Proceedings of the 2016 35th Chinese Control Conference (CCC), Chengdu, China, 27–29 July 2016; pp. 6109–6114.
75. Li, H.; Yao, J.; Zhou, P.; Chen, X.; Xu, Y.; Zhao, Y. High-force soft pneumatic actuators based on novel casting method for robotic applications. *Sens. Actuators A Phys.* **2020**, *306*, 111957. [CrossRef]
76. Fu, H.C.; Ho, J.D.L.; Lee, K.H.; Hu, Y.C.; Au, S.K.; Cho, K.J.; Sze, K.Y.; Kwok, K.W. Interfacing soft and hard: A spring reinforced actuator. *Soft Robot.* **2020**, *7*, 44–58. [CrossRef] [PubMed]
77. Hu, W.; Alici, G. Bioinspired three-dimensional-printed helical soft pneumatic actuators and their characterization. *Soft Robot.* **2020**, *7*, 267–282. [CrossRef]
78. Zhang, H.; Kumar, A.S.; Chen, F.; Fuh, J.Y.; Wang, M.Y. Topology optimized multimaterial soft fingers for applications on grippers, rehabilitation, and artificial hands. *IEEE/ASME Trans. Mechatron.* **2018**, *24*, 120–131. [CrossRef]
79. Liu, X.; Zhao, Y.; Geng, D.; Chen, S.; Tan, X.; Cao, C. Soft humanoid hands with large grasping force enabled by flexible hybrid pneumatic actuators. *Soft Robot.* **2021**, *8*, 175–185. [CrossRef] [PubMed]
80. Galloway, K.C.; Becker, K.P.; Phillips, B.; Kirby, J.; Licht, S.; Tchernov, D.; Wood, R.J.; Gruber, D.F. Soft robotic grippers for biological sampling on deep reefs. *Soft Robot.* **2016**, *3*, 23–33. [CrossRef] [PubMed]
81. Tawk, C.; Panhuis, M.I.H.; Spinks, G.M.; Alici, G. Bioinspired 3D printable soft vacuum actuators for locomotion robots, grippers and artificial muscles. *Soft Robot.* **2018**, *5*, 685–694. [CrossRef]
82. Zhang, Y.F.; Zhang, N.; Hingorani, H.; Ding, N.; Wang, D.; Yuan, C.; Zhang, B.; Gu, G.; Ge, Q. Fast-response, stiffness-tunable soft actuator by hybrid multimaterial 3D printing. *Adv. Funct. Mater.* **2019**, *29*, 1806698. [CrossRef]
83. Glick, P.; Suresh, S.A.; Ruffatto, D.; Cutkosky, M.; Tolley, M.T.; Parness, A. A soft robotic gripper with gecko-inspired adhesive. *IEEE Robot. Autom. Lett.* **2018**, *3*, 903–910. [CrossRef]
84. Li, Y.; Chen, Y.; Ren, T.; Choi, S.H. Precharged pneumatic soft actuators and their applications to untethered soft robots. *Soft Robot.* **2018**, *5*, 567–575. [CrossRef]
85. Crooks, W.; Vukasin, G.; O'Sullivan, M.; Messner, W.; Rogers, C. Fin ray® effect inspired soft robotic gripper: From the robosoft grand challenge toward optimization. *Front. Robot. AI* **2016**, *3*, 70. [CrossRef]
86. Chen, R.; Song, R.; Zhang, Z.; Bai, L.; Liu, F.; Jiang, P.; Sindersberger, D.; Monkman, G.J.; Guo, J. Bio-inspired shape-adaptive soft robotic grippers augmented with electroadhesion functionality. *Soft Robot.* **2019**, *6*, 701–712. [CrossRef] [PubMed]
87. Shahid, Z.; Glatman, A.L.; Ryu, S.C. Design of a soft composite finger with adjustable joint stiffness. *Soft Robot.* **2019**, *6*, 722–732. [CrossRef]
88. Ren, T.; Li, Y.; Xu, M.; Li, Y.; Xiong, C.; Chen, Y. A novel tendon-driven soft actuator with self-pumping property. *Soft Robot.* **2020**, *7*, 130–139. [CrossRef]

89. Li, H.; Yao, J.; Zhou, P.; Chen, X.; Xu, Y.; Zhao, Y. High-load soft grippers based on bionic winding effect. *Soft Robot.* **2019**, *6*, 276–288. [CrossRef] [PubMed]
90. Wang, Z.; Kanegae, R.; Hirai, S. Circular shell gripper for handling food products. *Soft Robot.* **2021**, *8*, 542–554. [CrossRef] [PubMed]
91. Brown, E.; Rodenberg, N.; Amend, J.; Mozeika, A.; Steltz, E.; Zakin, M.R.; Lipson, H.; Jaeger, H.M. Universal robotic gripper based on the jamming of granular material. *Proc. Natl. Acad. Sci. USA* **2010**, *107*, 18809–18814. [CrossRef]
92. Sholl, N.; Moss, A.; Kier, W.M.; Mohseni, K. A soft end effector inspired by cephalopod suckers and augmented by a dielectric elastomer actuator. *Soft Robot.* **2019**, *6*, 356–367. [CrossRef]
93. Bamotra, A.; Walia, P.; Prituja, A.V.; Ren, H. Layer-jamming suction grippers with variable stiffness. *J. Mech. Robot.* **2019**, *11*, 035003. [CrossRef]
94. Li, S.; Stampfli, J.J.; Xu, H.J.; Malkin, E.; Diaz, E.V.; Rus, D.; Wood, R.J. A vacuum-driven origami "magic-ball" soft gripper. In Proceedings of the 2019 International Conference on Robotics and Automation (ICRA), Montreal, QC, Canada, 20–24 May 2019; pp. 7401–7408.
95. Hao, Y.; Biswas, S.; Hawkes, E.W.; Wang, T.; Zhu, M.; Wen, L.; Visell, Y. A multimodal, enveloping soft gripper: Shape conformation, bioinspired adhesion, and expansion-driven suction. *IEEE Trans. Robot.* **2020**, *37*, 350–362. [CrossRef]
96. Althoefer, K. Antagonistic actuation and stiffness control in soft inflatable robots. *Nat. Rev. Mater.* **2018**, *3*, 76–77. [CrossRef]
97. Wang, L.; Yang, Y.; Chen, Y.; Majidi, C.; Iida, F.; Askounis, E.; Pei, Q. Controllable and reversible tuning of material rigidity for robot applications. *Mater. Today* **2018**, *21*, 563–576. [CrossRef]
98. Dou, W.; Zhong, G.; Cao, J.; Shi, Z.; Peng, B.; Jiang, L. Soft robotic manipulators: Designs, actuation, stiffness tuning, and sensing. *Adv. Mater. Technol.* **2021**, *6*, 2100018. [CrossRef]
99. Chen, R.; Zhang, Z.; Guo, J.; Liu, F.; Leng, J.; Rossiter, J. Variable stiffness electroadhesion and compliant electroadhesive grippers. *Soft Robot.* **2022**, *9*, 1074–1082. [CrossRef] [PubMed]
100. Mattmann, M.; De Marco, C.; Briatico, F.; Tagliabue, S.; Colusso, A.; Chen, X.Z.; Lussi, J.; Chautems, C.; Pane, S.; Nelson, B. Thermoset shape memory polymer variable stiffness 4D robotic catheters. *Adv. Sci.* **2022**, *9*, 2103277. [CrossRef]
101. Aksoy, B.; Shea, H. Multistable shape programming of variable-stiffness electromagnetic devices. *Sci. Adv.* **2022**, *8*, eabk0543. [CrossRef]
102. Babu, S.P.M.; Sadeghi, A.; Mondini, A.; Mazzolai, B. Antagonistic pneumatic actuators with variable stiffness for soft robotic applications. In Proceedings of the 2019 2nd IEEE International Conference on Soft Gripperics (RoboSoft), Seoul, Republic of Korea, 14–18 April 2019; pp. 283–288.
103. Crowley, G.B.; Zeng, X.; Su, H.J. A 3D printed soft robotic gripper with a variable stiffness enabled by a novel positive pressure layer jamming technology. *IEEE Robot. Autom. Lett.* **2022**, *7*, 5477–5482. [CrossRef]
104. Punera, D.; Mukherjee, P. Recent developments in manufacturing, mechanics, and design optimization of variable stiffness composites. *J. Reinf. Plast. Compos.* **2022**, *41*, 917–945. [CrossRef]
105. Arleo, L.; Lorenzon, L.; Cianchetti, M. Variable stiffness linear actuator based on differential drive fiber jamming. *IEEE Trans. Robot.* **2023**, *39*, 4429–4442. [CrossRef]
106. Hoang, T.T.; Quek, J.J.S.; Thai, M.T.; Phan, P.T.; Lovell, N.H.; Do, T.N. Soft robotic fabric gripper with gecko adhesion and variable stiffness. *Sens. Actuators A Phys.* **2021**, *323*, 112673. [CrossRef]
107. Gaeta, L.T.; McDonald, K.J.; Kinnicutt, L.; Le, M.; Wilkinson-Flicker, S.; Jiang, Y.; Atakuru, T.; Samur, E.; Ranzani, T. Magnetically induced stiffening for soft robotics. *Soft Matter* **2023**, *19*, 2623–2636. [CrossRef]
108. Jing, H.; Hua, L.; Long, F.; Lv, B.; Wang, B.; Zhang, H.; Fan, X.; Zheng, H.; Chu, C.; Xu, G. Variable stiffness and fast-response soft structures based on electrorheological fluids. *J. Mater. Chem. C* **2023**, *11*, 11842–11850. [CrossRef]
109. Xu, F.Y.; Jiang, F.Y.; Jiang, Q.S.; Lu, Y.X. Soft actuator model for a soft robot with variable stiffness by coupling pneumatic structure and jamming mechanism. *IEEE Access* **2020**, *8*, 26356–26371. [CrossRef]
110. Guo, X.Y.; Li, W.B.; Zhang, W.M. Adjustable stiffness elastic composite soft actuator for fast-moving grippers. *Sci. China Technol. Sci.* **2021**, *64*, 1663–1675. [CrossRef]
111. Han, F.; Fei, L.; Zou, R.; Li, W.; Zhou, J.; Zhao, H. A restorable, variable stiffness pneumatic soft gripper based on jamming of strings of beads. *IEEE Trans. Robot.* **2023**, *39*, 4065–4077. [CrossRef]
112. Le, H.M.; Phan, P.T.; Lin, C.; Jiajun, L.; Phee, S.J. A temperature-dependent, variable-stiffness endoscopic robotic manipulator with active heating and cooling. *Ann. Biomed. Eng.* **2020**, *48*, 1837–1849. [CrossRef] [PubMed]
113. Zhang, M.; Chen, X.; Sun, Y.; Gan, M.; Liu, M.; Tang, S.Y.; Zhang, S.; Li, X.; Li, W.; Sun, L. A magnetically and thermally controlled liquid metal variable stiffness material. *Adv. Eng. Mater.* **2023**, *25*, 2201296. [CrossRef]
114. Pagliarani, N.; Arleo, L.; Albini, S.; Cianchetti, M. Variable Stiffness Technologies for soft robotics: A Comparative Approach for the STIFF-FLOP Manipulator. *Actuators* **2023**, *12*, 96. [CrossRef]
115. Zhao, R.; Yao, Y.; Luo, Y. Development of a variable stiffness over tube based on low-melting-point-alloy for endoscopic surgery. *J. Med. Devices* **2016**, *10*, 021002. [CrossRef]

116. Wang, H.; Chen, Z.; Zuo, S. Flexible manipulator with low-melting-point alloy actuation and variable stiffness. *Soft Robot.* **2022**, *9*, 577–590. [CrossRef] [PubMed]
117. Lloyd, P.; Thomas, T.L.; Venkiteswaran, V.K.; Pittiglio, G.; Chandler, J.H.; Valdastri, P.; Misra, S. A magnetically-actuated coiling soft gripper with variable stiffness. *IEEE Robot. Autom. Lett.* **2023**, *8*, 3262–3269. [CrossRef]
118. Chung, H.J.; Parsons, A.M.; Zheng, L. Magnetically controlled soft robotics utilizing elastomers and gels in actuation: A review. *Adv. Intell. Syst.* **2021**, *3*, 2000186. [CrossRef]
119. Piskarev, Y.; Sun, Y.; Righi, M.; Boehler, Q.; Chautems, C.; Fischer, C.; Nelson, B.J.; Shintake, J.; Floreano, D. Fast-Response Variable-Stiffness Magnetic Catheters for Minimally Invasive Surgery. *Adv. Sci.* **2024**, *11*, 2305537. [CrossRef]
120. Mattmann, M.; Boehler, Q.; Chen, X.Z.; Pané, S.; Nelson, B.J. Shape memory polymer variable stiffness magnetic catheters with hybrid stiffness control. In Proceedings of the 2022 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Kyoto, Japan, 23–27 October 2022; pp. 9589–9595.
121. McDonald, K.J.; Kinnicutt, L.; Moran, A.M.; Ranzani, T. Modulation of magnetorheological fluid flow in soft robots using electropermanent magnets. *IEEE Robot. Autom. Lett.* **2022**, *7*, 3914–3921. [CrossRef]
122. Yin, X.; Yan, J.; Wen, S.; Zhang, J. Magnetorheological fluid-filled origami joints with variable stiffness characteristics. *IEEE/ASME Trans. Mechatron.* **2022**, *28*, 1546–1557. [CrossRef]
123. Kitano, S.; Komatsuzaki, T.; Suzuki, I.; Nogawa, M.; Naito, H.; Tanaka, S. Development of a rigidity tunable flexible joint using magneto-rheological compounds—Toward a multijoint manipulator for laparoscopic surgery. *Front. Robot. AI* **2020**, *7*, 59. [CrossRef] [PubMed]
124. Xu, Z.; Chen, Y.; Xu, Q. Spreadable magnetic soft robots with on-demand hardening. *Research* **2023**, *6*, 0262. [CrossRef] [PubMed]
125. Liu, C.; Busfield, J.J.C.; Zhang, K. An electric self-sensing and variable-stiffness artificial muscle. *Adv. Intell. Syst.* **2023**, *5*, 2300131. [CrossRef]
126. Wang, T.; Zhang, J.; Li, Y.; Hong, J.; Wang, M.Y. Electrostatic layer jamming variable stiffness for soft robotics. *IEEE/ASME Trans. Mechatron.* **2019**, *24*, 424–433. [CrossRef]
127. Avery, J.; Runciman, M.; Darzi, A.; Mylonas, G.P. Shape sensing of variable stiffness soft robots using electrical impedance tomography. In Proceedings of the 2019 International Conference on Robotics and Automation (ICRA), Montreal, QC, Canada, 20–24 May 2019; pp. 9066–9072.
128. Fasel, L.; Gerig, N.; Danun, A.; Meboldt, M.; Guzman, R.; Cattin, P.C.; Rauter, G. Antagonistic series elastic actuation for a variable stiffness robotic endoscope. *IEEE/ASME Trans. Mechatron.* **2024**, *29*, 1–11. [CrossRef]
129. Molaei, P.; Pitts, N.A.; Gilbert, H.B. Independent tendons increase stiffness of continuum robots without actuator coupling. In Proceedings of the 2023 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM), Seattle, WA, USA, 28–30 June 2023; pp. 72–78.
130. Yang, Y.; Wang, P.; Zhu, H.; Xia, K.; Ren, T.; Shen, Y.; Li, Y. A variable stiffness soft robotic manipulator based on antagonistic design of supercoiled polymer artificial muscles and shape memory alloys. *Sens. Actuators A Phys.* **2024**, *366*, 114999. [CrossRef]
131. Brancadoro, M.; Manti, M.; Tognarelli, S.; Cianchetti, M. Fiber jamming transition as a stiffening mechanism for soft robotics. *Soft Robot.* **2020**, *7*, 663–674. [CrossRef] [PubMed]
132. Brancadoro, M.; Manti, M.; Grani, F.; Tognarelli, S.; Menciassi, A.; Cianchetti, M. Toward a variable stiffness surgical manipulator based on fiber jamming transition. *Front. Robot. AI* **2019**, *6*, 12. [CrossRef] [PubMed]
133. Kang, J.; Lee, S.; Park, Y.L. Soft bending actuator with fiber-jamming variable stiffness and fiber-optic proprioception. *IEEE Robot. Autom. Lett.* **2023**, *8*, 7344–7351. [CrossRef]
134. Gao, Q.; Sun, Z. A novel design of water-activated variable stiffness endoscopic manipulator with safe thermal insulation. *Actuators* **2021**, *10*, 130. [CrossRef]