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Soft Robotic Grippers

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Advances in soft robotics, materials science, and stretchable electronics have enabled rapid progress in soft grippers. Here, a critical overview of soft robotic grippers is presented, covering different material sets, physical principles, and device architectures. Soft gripping can be categorized into three technologies, enabling grasping by: a) actuation, b) controlled stiffness, and c) controlled adhesion. A comprehensive review of each type is presented. Compared to rigid grippers, end-effectors fabricated from flexible and soft components can often grasp or manipulate a larger variety of objects. Such grippers are an example of morphological computation, where control complexity is greatly reduced by material softness and mechanical compliance. Advanced materials and soft components, in particular silicone elastomers, shape memory materials, and active polymers and gels, are increasingly investigated for the design of lighter, simpler, and more universal grippers, using the inherent functionality of the materials. Embedding stretchable distributed sensors in or on soft grippers greatly enhances the ways in which the grippers interact with objects. Challenges for soft grippers include miniaturization, robustness, speed, integration of sensing, and control. Improved materials, processing methods, and sensing play an important role in future research.

1. Introduction

Grasping and manipulation are fundamental functions of both animals and robots. A simplified description of grasping is the ability to pick up and hold an object against external disturbances, while manipulation is the ability to exert forces on an object and thus cause its rotation and displacement with respect to the reference frame of the manipulator. In addition to grasping and manipulation, animals and robots may use their end effectors for other actions, such as locomotion, perching, digging, sorting, scratching, and many more. Furthermore, these end effectors can gather sensory information about the physical properties of the objects. In this article, we use the word "gripper" to indicate robotic end effectors that can provide one or more of those functionalities.

Traditional robotic grippers consist of a set of mostly rigid joints and links.[1] Actuators can be housed within the links, within the joints, or at the gripper base by means of cables or tendon-like structures. Robotic grippers can be equipped with proprioceptive sensors (e.g., Hall-effect sensors, encoders, torque sensors, tendon tension sensors) to estimate position and velocity of the gripper elements, and with exteroceptive sensors (e.g., pressure sensors, optical sensors, resistive and conductive sensors, electromagnetic sensors) to gather information about the objects. Gripper designs range from two-fingered grippers all the way to anthropomorphic hands with articulated fingers and palm. The choice of anthropomorphic grippers is often motivated by the quest for flexibility and dexterity of human hands, by the need of being compatible with the human environments, or by the tele-operation with smart gloves. Although several impressive anthropomorphic grippers have been recently described,[2] they still present challenges, such as the high mechanical and control complexity required to achieve the speed, flexibility, and dexterity of human hands and the difficulty in handling soft and deformable objects. Recently, more compliant and mechanically simpler, anthropomorphic grippers have been described that resort to flexible and partly soft components.[3,4] These grippers are often cited as an example of morphological computation where control complexity is reduced by material softness and mechanical compliance.[5]

Advanced materials and soft components are increasingly studied for the design of lighter, simpler, and possibly more universal grippers. The importance of compliance in grasping has long been recognized. Unless very carefully controlled, making contact between a hard gripper and a hard object leads to shocks that could damage the object or push it out of the desired path. A simple but only partial solution, widely employed in robotic end effectors, is to add compliant materials to the gripping elements (for instance in the simple form of rubber pads).

Contact between bodies introduces constraints to the movement of those bodies. For this reason, underactuation (i.e., having a higher number of degrees of freedom than the number of actuators) is essential for grippers, since it can allow them to conform to the objects' shape without active position control. Human fingers are an example of such underactuation,

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each one consisting of one tendon and three links (two degrees of freedom). Soft grippers integrate underactuation and compliance by replacing rigid joints with a structure made of hyperelastic materials that deform continuously in response to external or internal actuators and to the interaction with the objects.

Compliant materials thus play a key role in soft grippers: material characteristics such as maximum elastic deformation, stiffness and viscoelasticity influence the stroke of the gripper, the force it can generate, and its response time. The selection and engineering of materials is therefore central in the design of soft grippers with enhanced capabilities.

The most widely used materials for soft grippers are elastomers, thanks to the large strains they can reversibly sustain (>100%). Silicone rubbers have been the most popular choice for grippers thanks to their ease of fabrication, low toxicity, robustness, and low mechanical damping coefficients. For instance, they are used to fabricate grippers based on fluidic elastomer actuators (FEAs), often with the addition of reinforcing fibers. Combining conductive and dielectric silicones enable grippers based on dielectric elastomer actuators (DEAs), which can also feature electroadhesion.

Materials that change their properties in response to stimuli can greatly expand the functionalities of soft grippers. An example is materials whose stiffness varies in response to temperature, such as shape memory alloys (SMAs), shape memory polymers (SMPs), and low-melting point alloys (LMPAs). These materials have been used both as actuators and as holding elements in grippers based on controlled stiffness, exploiting their soft state to conform to the object's shape and their rigid state to generate high forces. Other ways to achieve controlled stiffness include materials that react to electric and magnetic stimuli and materials in granular form (particle jamming). Researchers have explored materials able to respond to several other stimuli, for instance pH, chemical concentration, humidity, or light. Ionic materials are another class of advanced materials used in soft grippers. These materials can serve as actuators in response to an applied electric field, as in the case of ionic polymer-metal composites (IPMCs), or can be used to build grippers that are invisible in aqueous environments, as in the case of hydrogels. Surface conditions are very important for soft grippers. Biocompatibility and food safety are required in the health and food sectors. Micro- and nanopatterned surfaces enable gripping by dry adhesion. Finally, the increasing pressure for environmentally compliant technologies has induced researchers to explore soft grippers made of biodegradable, and even edible, materials.

Figure 1 is an abridged timeline of milestones in the development of soft gripper technologies, starting with tendon-driven multilink devices in the 1970s, then extending to other gripping modalities in the 1980s and 1990s, with improved concepts, materials and methods. The 2000s saw the emergence of electroactive polymers and increased used of elastomers, granular jamming and fluidic elastomer actuators. The rapid progress in soft robotics[6–9] in this decade leads to further improvements in gripper performance and robustness, and recently to the commercialization of soft grippers. Soft grippers can operate on a large variety of objects of diverse shapes, textures and consistencies. Soft grippers have enabled the increasing automation of many tasks deemed previously to be far too delicate for robotic manipulation.

In this article, we provide a critical overview of the broad field of soft robotics grippers, covering different material sets, physical principles, and device architectures.

2. Gripper Technologies

We have categorized soft gripping in three technologies: i) by actuation (Section 3), ii) by controlled stiffness (Section 4), and iii) by controlled adhesion (Section 5). These three categories are not exclusive, and many devices make use of combinations of two technology classes to reach higher performance. The preferred technology and materials for a given task will depend on properties of the object being manipulated, the operating environment (e.g., wet, dry, clean), required force, required speed, permissible power consumption and weight, biocompatibility, as well as system constraints including the integration or use of external sensors, and control methods. Since soft grippers provide excellent shape adaptation to a broad range of objects, control is dealt with differently than for more conventional grippers based on rigid technologies.

Table 1 provides an overview of some key performance metrics for soft grippers, based on published results. While the

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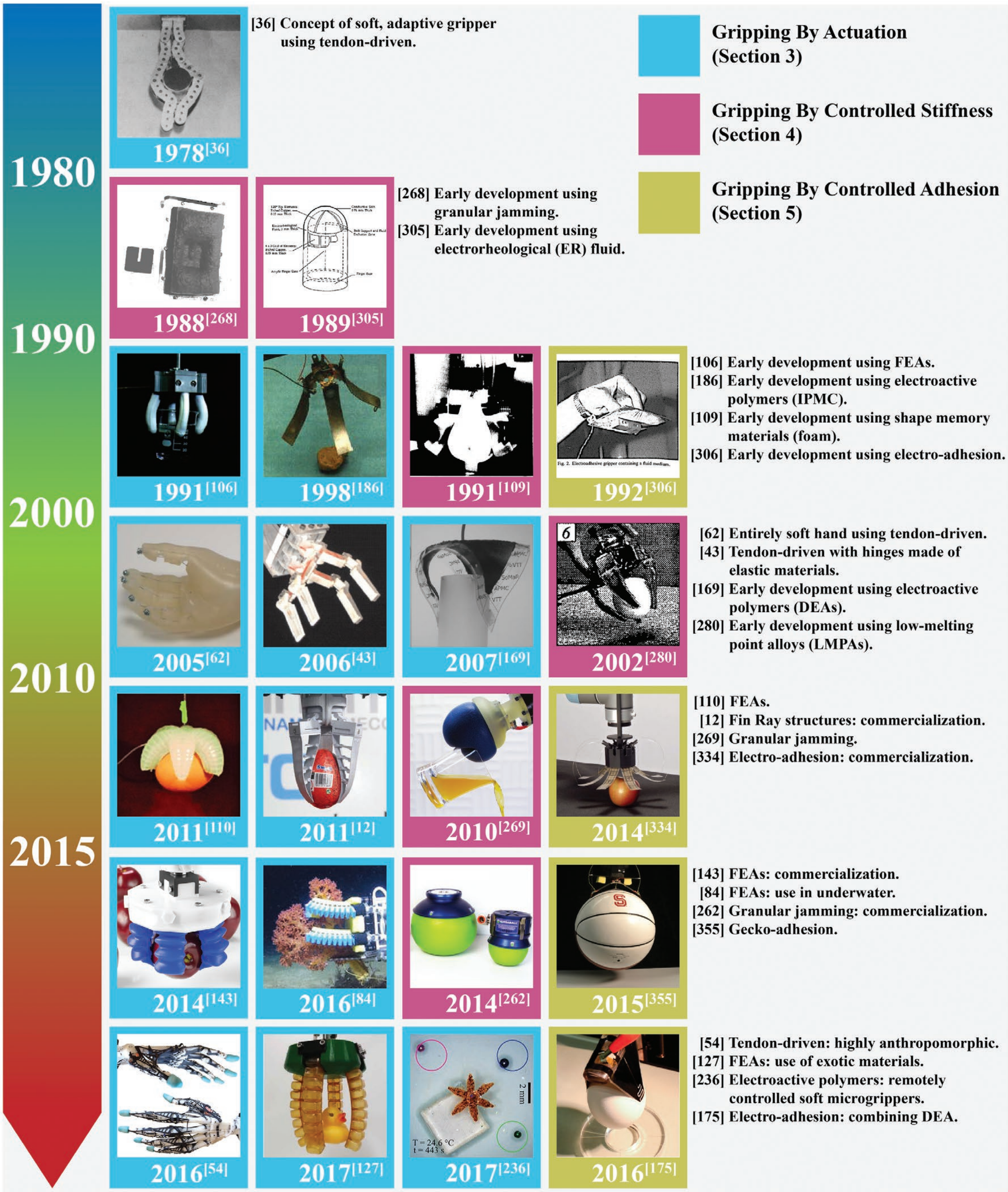

Figure 1. (1970s) Soft gripper were demonstrated using rigid multilink and tendon-driven. Reproduced with permission.[36] Copyright 1978, Elsevier. (1980s) Early developments of grippers using granular jamming and ER fluid. Reproduced with permission.[268] Copyright 1988, Heinz Weißmantel. Reproduced with permission.[305] Copyright 1989, IEEE. (1990s) Developments of grippers using FEAs, IPMCs, shape memory materials, and electro-adhesion. Reproduced with permission. Image leftmost, Copyright Koichi Suzumori. Reproduced with permission. Image second from the left, Copyright Yoseph Bar-Cohen. Reproduced with permission.[109] Copyright 1991, IEEE. Reproduced with permission.[306] Copyright 1992, Cambridge University Press. (2000s) Tendon-driven grippers with compliant materials were developed (entirely soft structure and elastic hinges). Early developments on grippers were performed using DEAs and LMPAs. Reproduced with permission.[62] Copyright 2005, IEEE. Reproduced with permission.[43] Image courtesy of Aaron M. Dollar. Reproduced with permission.[169] Copyright 2007, AIP. Reproduced with permission.[280] Copyright 2002, IEEE. (2010s) Revisiting the early developments and commercialization. Extension of application to underwater (FEAs), use of exotic materials (FEAs), and of gecko adhesion. Reproduced with permission.[12] Copyright 2011, Emerald Publishing. Reproduced with permission. Copyright 2010, John Amend. Reproduced with permission.[334] Copyright Grabit Inc. Reproduced with permission.[143] Copyright Soft Robotics Inc. Reproduced with permission.[84] Copyright 2016, Mary Ann Liebert. Reproduced with permission.[262] Copyright 2016, Mary Ann Liebert. Reproduced with permission.[355] Copyright 2015, IEEE. Reproduced with permission.[54] Copyright 2016, IEEE. Reproduced with permission.[127] Copyright 2017, AAAS. Reproduced with permission.[236] Copyright 2016, The Authors, published by Springer Nature.

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Table 1. Comparison of soft gripper performance for different grasping technologies.

Category[a)]	Technology	Lifting ratio Object mass / gripper mass	Gripper size[f)] [10^{-2} m]	Object size [10^{-2} m]	Response time[b)] [s]	Power consumption [W]	Surface conditions Any (A), Dry (D), Clean (C)
Actuation	Passive structure with external motors	4.5[49]c)–16.3[46]c)	1.2[34]–15.8[49]	0.01[34] to ≈60[44]	N/A	10^{1}	(A)
	Fluidic elastomer actuators (FEAs)	2[4]–68[77]	0.5[138]–120[133]	0.1[138] to ≈100[72]	0.1[132]–6[105]	10^{1}[d)]	(A)
	Electroactive polymers: dielectric elastomer actuators (DEAs)	8.7[171]	2[173]–10.3[171]	≈1[173] to ≈8[171]	0.1[171]–1[173]	10^{-1}[e)]	(A)
	Electroactive polymers: Ionic polymer-metal composites (IPMCs)	2[185]–3.5[187]	0.5[187]–8[186]	0.1[187] to ≈4[186]	1[189]–10[186]	10^{-1}	(A)
	Shape memory materials: shape memory alloys (SMAs)	15[212]–25.8[213]	0.9[216]–11.5[210]	0.2[219] to ≈20[212]	0.67[212]–11[213]	10^{0}	(A)
Controlled Stiffness	Granular jamming	7.6–15.1[262]	4.3[261]–35.5[265]	0.43[261] to ≈30[269]	0.1[262]–1.1[261]	10^{1}[d)]	(A)
	Low melting point alloys (LMPAs)	2.2[280]–5.5[174]	3.5[174]–9[280]	≈5[174]–12[280]	30[174]–40[91]	10^{0}	(A)
	Electro-rheological (ER) and magneto-rheological (MR) fluids	N/A	≈5[308]	≈5[308]	0.001[305]–0.46[308]	10^{-1}(ER), 10^{0}(MR)	(A)
	Shape memory materials: Shape memory polymers (SMPs)	30[320]–925[244]	≈0.5[200]–15.6[322]	≈0.5[200]–8[319]	5[320]–60[89]	10^{0}	(A)
Controlled Adhesion	Electro-adhesion	54.7[175]	3[336]–4.8[175]	3[336] to ≈100[335]	0.1[175]	10^{-1}[e)]	(D), (C)
	Geckoadhesion	39[360]–286.7[355]	1.8[358]–8[355]	0.16[95] to ≈60[355]	0.09[355]	N/A	(D), (C)

[a)]Values do not reflect exact the ultimate limits of each technology, but rather the best results published to date. For more details of performance on the actuation, controlled stiffness, and adhesion technology, see refs. [19,52,71,151,253,363] and Sections 3, 4, 5; [b)]Grasping time; [c)]Gripper mass includes entire hand; [d)]Including pressure generator; [e)]Including high-voltage dc/dc converter; [f)]Length of finger/manipulator or diameter of bag.

numbers in the table do not reflect ultimate performance limits of the selected technologies, they do provide a quantified means of comparing the different technologies, in terms of lifting ratio (the ratio of object mass to gripper mass), gripper and object size, speed, power consumption, and requirements on surface conditions. Different size scales have different preferred operating principles due to scaling laws.

Figure 2 provides a qualitative overview of the suitability of the three different gripper technologies for different object shapes (e.g., flat objects are easy to pick up using controlled adhesion, but not using variable stiffness).

Gripping by actuation consists of bending gripper fingers or elements around the object, as we do with our fingers when picking up an egg or glass of water. The bending shape can be actively controlled, or one can exploit contact with the object to induce deformation. Of the many approaches, those with external electromagnetic motors and FEAs are the most mature, with many devices shown in past 30 years. These techniques work well in air and in water, and are not overly sensitive to surface conditions or surface energy. There remain many challenges for gripping by actuation, including obtaining sufficient forces, controlling force and force distribution, especially for handling deformable objects. Flat objects are not suited to this method.

Gripping using controlled stiffness exploits the large change in rigidity of some materials or material combinations to hold an object. An actuator is needed to envelop the object with part of the gripper, but as the gripper is in the soft state, the actuation force can be very low, allowing very delicate objects to be caged. Key examples are phase change materials such as shape memory polymers and low-melting point alloys, granular jamming, and electrorheological (ER)/magnetorheological (MR) fluids. Such grippers can be fast and allow tuning of the stiffness to a desired level. Limitations are the range of stiffness change that can be achieved, and for thermal systems the time constants can be long.

Gripping using controlled adhesion, like variable stiffness, requires an actuation method to partially envelop the object. Controlled adhesion by electroadhesion or dry adhesive (the so-called geckoadhesive) relies on surface forces at the interface between gripper and object. This operating principle is a major advantage when manipulating very delicate objects, as it avoids the high compressive forces required in gripping by actuation, because one can obtain high shear forces without exerting large overall normal forces on object. Controlled adhesion is also ideal for flat objects or objects that cannot be enveloped. Limitations include requiring clean and relatively smooth and dry surfaces.

Overall challenges for soft grippers include robustness, speed, integration of sensing, and control. Improved materials (elastomers, phase change materials) and processing methods play a large role in future improvements.

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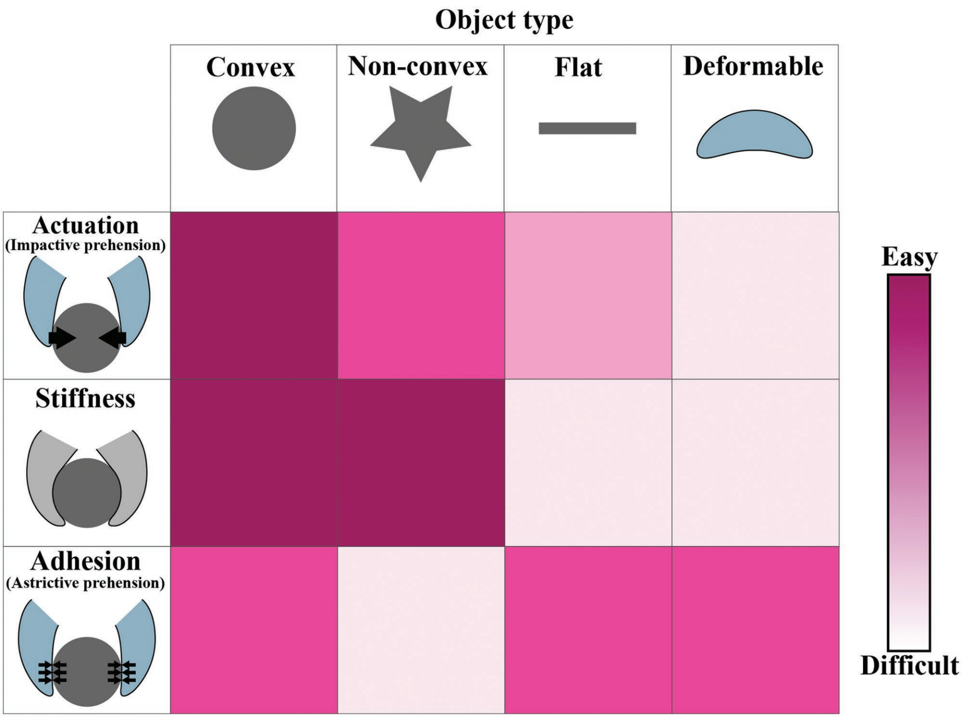

Figure 2. One possible classification of the characteristics of soft grippers for different gripping technologies and object types.

3. Gripping by Actuation

In soft grippers, grasping of an object can be performed through the adaptation of compliant structures deformed by external or integrated actuators. Researchers have investigated soft grasping by actuation in many different ways. Here, we focus our review on the representative actuators technologies listed in **Figure 3**: passive structure with external motors (Section 3.1), fluidic elastomer actuators (Section 3.2), electroactive polymers (Section 3.3), and shape memory materials (Section 3.4). The deformation of passive structures can either exploit the reaction forces arising from the contact with the object (Figure 3a), or derive from the pulling of embedded cables (Figure 3b). Fluidic elastomer actuators rely on the inflation of their elastomeric chambered structure, whose deformation is shaped through the use of asymmetric geometries or reinforcing fibers (Figure 3c). Electroactive polymers, such as dielectric elastomer actuators (Figure 3d) and ionic polymer-metal composites (Figure 3e), actively deform in response to electrical stimuli. The shape memory effect of some materials can be also used as a means of soft grasping actuation. Major materials of this type include shape memory alloys (Figure 3f) and shape memory polymers (Figure 3g). At the end of this section, we will also review some other active materials applied to soft grippers (Section 3.5). We exclude piezo-ceramic materials from our review, due to their inherent high rigidity and low strains limiting their use in adaptive grasping.

3.1. Passive Structure with External Motors

Soft grasping can be achieved by compliant structures that are moved by external electromagnetic motors and passively adapt to the shape of the object. The main feature of this method lies in the absence of active elements inside the gripper structure in contact with the object. Hence, high mechanical robustness can be achieved. Additionally, since the motor is external, its size and weight are mostly independent from the geometry of the gripper itself, providing a wide selection range. It is therefore possible to obtain high forces by choosing suitable high-torque motors. As a mature technology, the use of electromagnetic motors also provides ease of integration with electronics and well-known control methods. These features make the implementation and building of the gripper system simpler on a practical level. As a consequence, soft grippers consisting in passive structures and external motors are widely used in industry and robotics.

We can distinguish between two main types of externally motorized soft grippers. The first one relies on the contact with the object to trigger the deformation of gripper structure, which results in grasping. We call it contact-driven deformation (Figure 3a). The second one consists in tendon-driven grippers, for which the actuation is transmitted through cables embedded in the structure. Most of these grippers are made by articulated fingers (Figure 3b). In this section, we focus on the review of these two categories, contact-driven deformation and tendon-driven, which can be found in Sections 3.1.1 and 3.1.2, respectively. We will discuss challenges and future work at the end of Section 3.1.2.

3.1.1. Contact-Driven Deformation

The passive deformation of a compliant structure forced by external mechanical inputs can be used as a strategy for

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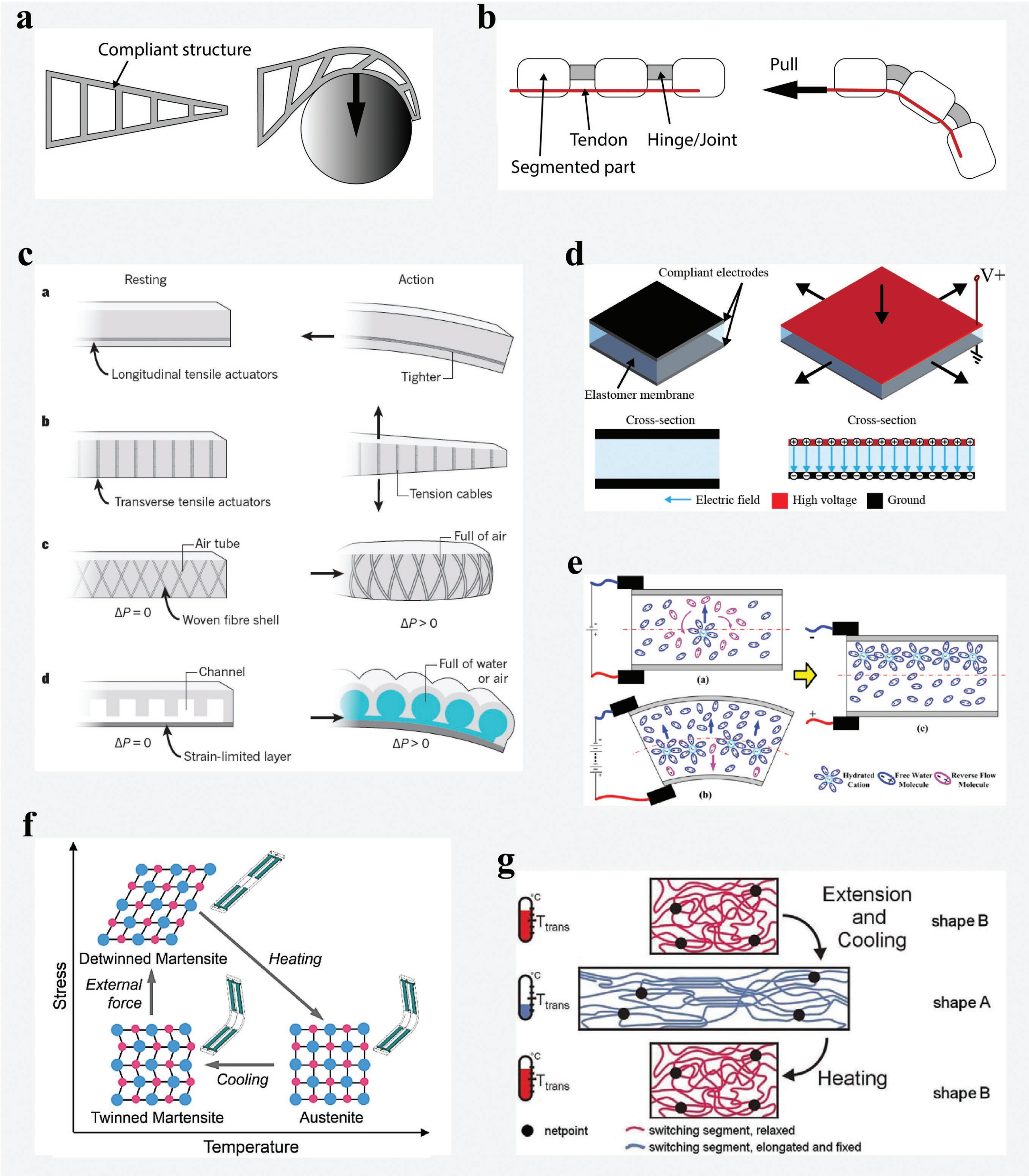

Figure 3. Working principle of technologies for soft grasping. a) Contact-driven deformation (Fin Ray structure). b) Tendon-driven. c) Fluidic elastomer actuators (FEAs). Reproduced with permission.[8] Copyright 2015, Springer Nature. d) Dielectric elastomer actuators (DEAs). e) Ionic polymer-metal composites (IPMCs). Reproduced with permission.[400] Copyright 2013, IOP Publishing. f) Shape memory alloys (SMAs). Reproduced with permission.[210] Copyright 2016, Elsevier. g) Shape memory polymers (SMPs). Reproduced with permission.[401] Copyright 2007, Elsevier.

grasping. One representative example of such passive structures is the Fin Ray, which is inspired from the deformation of fish fins.[10] When the structure touches an object, it bends, conforming to the surface, grasping in response to the reaction forces (Figure 3a). Grippers based on this method are actuated by external servomotors providing rotation or parallel

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movements of the grasping parts. Including an example shown in **Figure 4**a,[11] several Fin Ray grippers have been developed, which have been used to handle a wide range of items including a ball, an egg, a fruit, a tulip bulb, tools, and office supplies.[12–14] Harvesting vegetables in a greenhouse has been shown,[15] and the company bionicTOYS produced gripper toys using the Fin Ray structure (Figure 4b).[16] Sensing elements were implemented in these structures using 3D printed conductive circuits to obtain contact information.[17]

Passive structures can also be combined with rigid systems as end-effectors in the form of pads,[18–22] fingertips,[23] threads,[24] and strips.[25] In some cases, passive grasping structures can even take the role of locomotion units, as in the example of an octopus robot developed by Sfakiotakis et al.[26] There are also developments showing the encapsulation of functional materials inside the passive structures, such as smart fluids and particles to enable controlled stiffness, which are discussed in Section 4. Compliant mechanisms provide an additional method to exploit passive structural deformation for grasping. They are composed of flexible beams with monolithic or articulated structures.[27–30] The essential difference with respect to the previous examples is that, in compliant mechanisms, the actuation consists of a simple movement of the base of the gripper and the grasping action results from bending and/or buckling of the structure (Figure 4c). Liu et al.[30] showed that with the aid of topological optimization, a gripper of this kind was able to handle diverse objects including a PCB, a USB flash drive, marble, clips, a battery, and coins (Figure 4d). Issa et al.[31] embedded resistive sensing elements made of a conductive silicone elastomer into the connections of a compliant mechanism, and showed that it was possible to detect the presence of the object being held. Due to the simplicity of the structure, compliant mechanisms are also suitable for microgrippers.[32–35]

3.1.2. Tendon-Driven

Inspired by human fingers, tendon-driven underactuated structures have been widely employed in robotic hands and grippers. They generally consist of a multi degree of freedom articulated body actuated by a single tendon. Traditionally, grippers using this actuation method consisted of rigid links, joints, and springs.[36–42] In this section, we will focus on reviewing tendon-driven grippers incorporating soft materials.

One approach is to use hinges made of elastic materials, leading to simpler systems compared to rigid joints with mechanical springs.[43–50] Elastic hinges allow exploiting stored bending energy to return the actuated fingers to their initial position. Figure 4e is an example of such compliant tendon-driven grippers that demonstrated grasping of a wide range of items from a plastic bottle to a glass cup.[50] The fingers of the devices are made of 3D printed segments and rubber flexure joints that are monolithically integrated by molding process. This technique also enables integration of tactile and bending sensors.[46,51]

Mimicking the structure of the human hand by using rigid and elastic parts to resemble bones and tissues respectively, anthropomorphic design was used to build tendon-driven grippers.[52–54] The concept aimed to achieve the high dexterity provided by the biomechanics of the human hand. Figure 4f displays an anthropomorphic hand developed by Xu and Todorov[54] which faithfully mimics geometry of bones and placement of muscles and tendons. Thanks to the biomimetic structure, the device showed many types of grasping categorized according to hand taxonomy.[55] Another approach combines the use of soft materials and a dedicated control paradigm in an anthropomorphic hand where the rigid tendons have been replaced by elastic ligaments.[3]

A compliant skin, like that of human hands, can improve the friction of tendon-driven grippers with objects for better handling.[56–58] Another benefit of skins is that they can be sensorized to obtain pretouch and contact information of the object, useful for selecting grasping patterns. Tavakoli et al.[59] made a robotic hand whose fingers are covered with capacitive sensors made of elastomers (Figure 4g). Triggered by information about the object obtained through the distributed sensors, the hand displayed different closing patterns according to the object type.

Fabricating the conventionally rigid elements of tendon-driven systems using soft materials is a promising approach. Such grippers have been developed by replacing both the articulated segments and the joints with elastomers.[60,61] Carrozza et al.[62] presented a robotic hand made of a monolithic, molded structure (Figure 1). They employed a silicone elastomer (Dow Corning Sylgard 186) to realize an entirely compliant structure. Other researchers also demonstrated soft cable-driven grippers by placing cables inside an elastomeric bag,[63] textiles,[64] and origamis,[65] similar to continuum tendon-driven manipulators.[66] Calisti et al.[67] demonstrated the grasping of a pencil and screws by a tendon-driven elastomeric manipulator inspired by the Octopus arm (Figure 4h), which was later implemented in a robot capable of locomotion and object manipulation.[67] An interesting example is shown in Figure 4i.[63] This gripper consists of a compliant elastomeric bag that is actively deformed by the tendon pulling the central bottom of the structure. The device is successful at lifting up of numerous objects such as cups and tools.

A potential limitation of soft grippers using external motors is the difficulty of miniaturization of the entire system, which can limit the use of the technology in compact mobile platforms. Since the mechanics of such grippers and the external electromagnetic actuators are both well established, future work can be expected to be mostly in control. As an example, Catalano et al.[3] proposed the concept of soft synergies for the control of an underactuated hand with compliant cables. Furthermore, miniaturization could be achieved by substituting electromagnetic motors with more compact actuators, such as smart materials. In this regard, researchers have showed the integration of shape memory alloys into tendon-driven fingers and grippers.[68–70]

3.2. Fluidic Elastomer Actuators

FEAs (also referred to as soft pneumatic actuators) are among the oldest but still today the most widespread actuation technologies for soft robotics due to a number of advantages,

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Figure 4. Soft grippers using passive structure with external motors. a) Fin Ray robotic gripper.[11] Reproduced with permission. Copyright Festo AG & Co. KG. b) Fin Ray (toy). Reproduced with permission.[16] Copyright BionicToys GmbH. c) Working principle of compliant mechanism. Reproduced with permission.[28] Copyright 2013, Emerald Publishing. d) Compliant mechanism. Reproduced with permission.[30] Copyright 2017, Springer Nature. e) Tendon-driven with elastic hinges. Reproduced with permission.[50] Copyright 2017, IEEE. f) Anthropomorphic tendon-driven. Reproduced with permission.[54] Copyright 2016, IEEE. g) Tendon-driven with sensor embedded soft skin. Reproduced with permission.[59] Copyright 2017, IEEE. h) Tendon-driven elastomeric manipulator. Reproduced with permission.[67] Copyright 2011, IOP Publishing. i) Tendon-driven with a compliant elastomeric bag. Reproduced with permission.[63] Copyright 2016, IEEE.

including easy fabrication, robustness, and low cost elastomer materials.[9,71] Actuation is obtained through the pressure exerted by a fluid (liquid or gas) on a chamber made by highly deformable materials (Figure 3c). The structures of FEAs are generally asymmetric by geometry or anisotropic by materials so that the inflation of the chamber is converted into a bending of the whole actuator. FEAs can generate high forces, which are proportional to the pressure of the fluid and to the surface area where the active pressure is applied. For example, blocked forces of 80 N at 300 kPa and 112 N at 200 kPa have been reported.[72,73] Fluidic based systems can have extremely large strokes as they are limited mainly by the maximum strain that the material can reliably sustain. Bending FEAs can reach bending angles around 300° in a reaction time of ≈0.05 s to 1.0 s.[74,75] The reaction time depends on the pressure-flow rate characteristic of the pump/compressor, on the internal volume of the chamber and on the stiffness of the elastomer.

There exist numerous architectures for FEAs. The most common ones include: elongated elastomeric chambers with the addition of reinforcing fibers and layers, bellows-like structures, and tube-like tentacles.[9,71] Fabrication of FEAs relies generally on the molding of the elastomer constituting the chamber. The molding process, dealing with the material in its liquid form, offers the possibility of incorporating functional elements in the actuator such as fibers,[76–79] inextensible layers (e.g., papers and fabrics),[74,80,81] porous materials,[82–85] origamis,[80] variable stiffness elements,[86–94] adhesion,[95] and strain sensors.[96–105]

Pioneering soft grippers in the early 1990s were developed using FEAs, as represented by the four-fingered gripper developed by Suzumori et al., shown in **Figure 5**a.[106,107] Each finger, 12 mm in diameter and composed of three pneumatic chambers, can bend in any direction, resulting in dexterous grasping able to manipulate various objects (e.g., a beaker filled with liquid, a metallic wrench) and even able to tighten a small bolt without the use of tools. Another example of gripper at larger scale is composed of three FEA fingers and can manipulate a copper pipe and a fragile light bulb.[108] Monkman and Taylor developed pneumatically actuated fingers made of a shape memory foam and performed the handling of a fruit (Figure 1).[109] Dohta et al. made soft fingers using fibers as radial constraint to the expansion of the chamber and a longitudinal plastic sheet to turn the elongation into bending.[104,105] Using an electroconductive carbon paste, they equipped each finger with a resistive strain sensor. Their four-fingered hand lifted a weight up to 20.8 N and manipulated a soft piece of tofu.

Following the early developments, new materials, processing methods and device configurations were developed. Figure 5b presents a gripper composed of three layers using the so-called PneuNets, bending FEAs fabricated using soft lithography.[110] This 6-fingered gripper could bend both upward and downward and was able to pick up a raw egg and a live anesthetized mouse. Rather than using traditional compressors or syringes, Yamaguchi et al.[111] developed a robotic hand actuated through rigid but integrated electrohydrodynamic[112] (EHD) units (Figure 5c). Using one unit for each of the five fingers, the hand held a small and a large cup and a tape roll with a mass of 12.7 g. Fiber-reinforced FEAs led to the development of a bioinspired soft hand able to mimic various human grasps and to manipulate everyday objects such as bottles, pens, sunglasses (Figure 5d).[4,76] A bellows-like gripper employed structural reinforcement of a silicone elastomer with polyaramid fibers to increase the tear resistance and obtain self-healing over small punctures.[113] Bending bidirectionally using positive or negative pressure, the gripper was able to lift a wine glass by picking it either from the inside or the outside. Various application fields have been proposed for soft grippers made by FEAs. Low et al.[114] used two fingers to manipulate a surgical wire. Galloway et al.[84] showed the manipulation of delicate deep reefs (Figure 1) and Zhou et al.[115] reported picking up of various food items, such as a banana, a pear, a piece of tofu, and an egg, using the integration of special materials in the palms of the grippers: a memory foam sheet and a patterned elastomeric layer. Manipulation of objects in amphibious environment was demonstrated by Hao et al.[116]

Researchers demonstrated rapid fabrication through printing of FEA-based grippers. Figure 5e shows a hand using pneumatic pouch motors and a flexible structure that can be printed in 15 min.[117] MacCurdy et al.[118] developed a two-fingered gripper by inkjet printing of a soft elastomer. A customized 3D printer (layer resolution 0.1 mm) using fusion deposition molding of a commercial thermoplastic elastomer, was used to fabricate a four-fingered gripper, able to lift a chair of 3.2 kg of mass.[72] Another 3D printed gripper performed handling of different types of food filled in paper containers.[119,120] Patel et al.[121] and Thrasher et al.[122] demonstrated a 3-fingered gripper made of UV curable elastomers that are 3D printed through digital light processing.

In order to expand the functionality of the grippers, researchers have integrated functional elements in their structure, exploiting the versatility offered by the molding process. Curvature sensing was implemented using resistive strain sensors made of stretchable or flexible electrodes,[96,97,100–105] stretchable optical waveguides,[98] as well as force sensing using a piezoresistive fabric component.[123] The integration of variable stiffness elements can offer increased holding weight. The proposed solutions include particle jamming,[88,93] shape memory polymers,[89] thermoplastic ligaments,[92] and low-melting point alloys.[91] Hao et al.[124] manually added a nylon wire around the fingers of the gripper to change their functional length and handle objects of different sizes, such as a screw, a pen, a chain of keys and a cactus.

Recently, materials that are highly unconventional for robotics have been used for FEAs grippers. Figure 5f shows the use of hydraulically actuated hydrogels to obtain a gripper that is optically and sonically camouflaged in water, as demonstrated by the capture and release of a living goldfish.[75] Walker et al.[125] used a biodegradable elastomer, i.e., poly(glycerol sebacate) with calcium carbonate, to develop an environmentally safe device, while Shintake et al.[126] achieved even an edible gripper using a gelatin–glycerol material. Terryn et al.[127] addressed self-healing based on thermo-reversible Diels–Alder polymers (Figure 5g).

In additions to the use of bending fingers, researchers have demonstrated FEAs in different configurations. Yang et al.[128] connected two passive fingers to a bladder containing chambers that collapse due to negative pressure, generating the opening of the gripper. Al Abeach et al.[129] employed elongating and contracting McKibben muscles in an antagonistic configuration, achieving a force of 10N at 400 kPa. The use of multifilament McKibben actuators (measured contraction force of 70 N) as muscles, allowed Faudzi et al.[130] to develop a robotic

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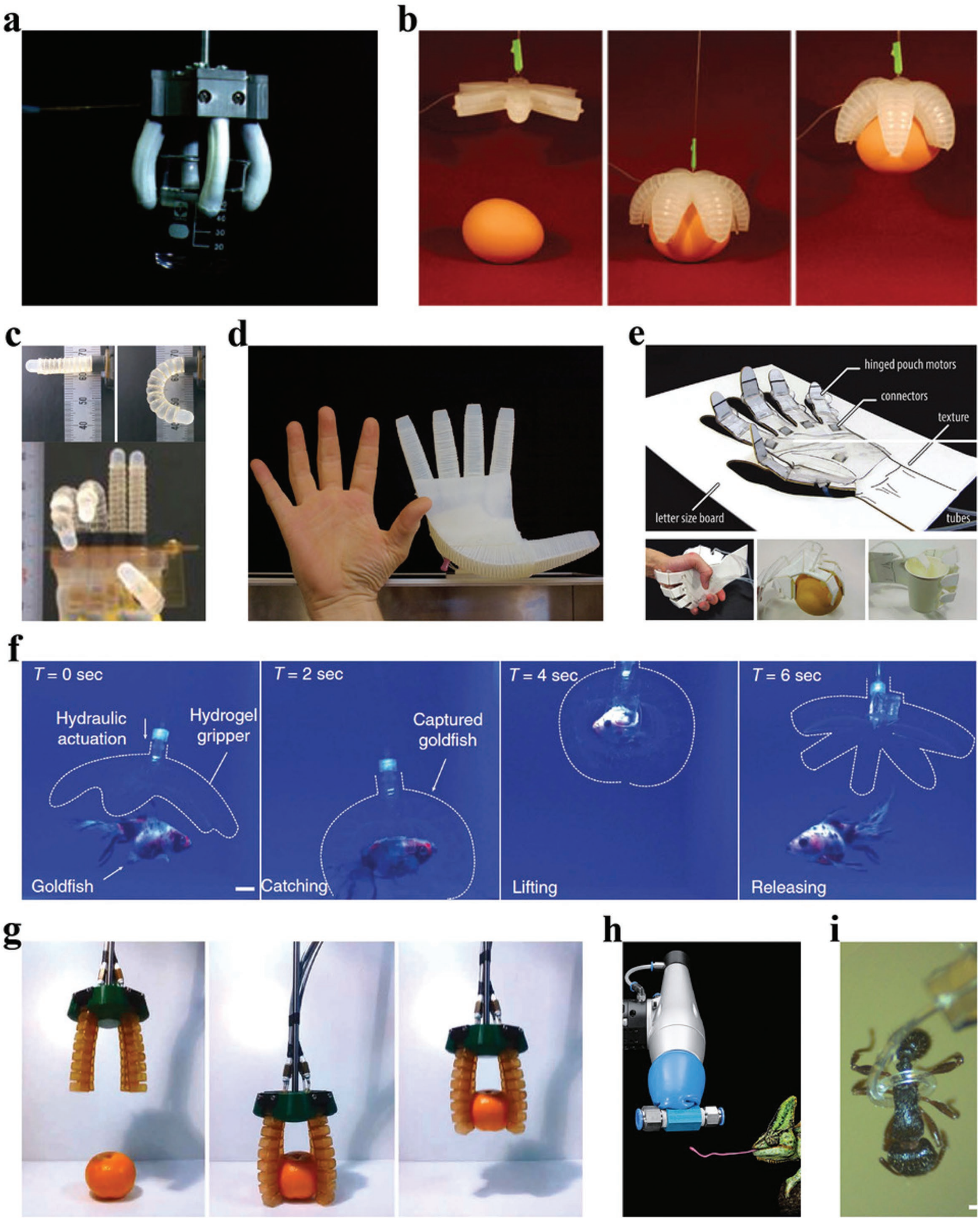

Figure 5. Soft grippers using fluidic elastomer actuators (FEAs). a) Multichambered fingers.[106,107] Reproduced with permission. Copyright Koichi Suzumori. b) PneuNets.[110] c) Fingers actuated by electrohydrodynamics. Reproduced with permission.[111] Copyright 2011, Elsevier B.V. d) Bio-inspired hand.[4] Reproduced with permission. Copyright Raphael Deimel. e) Pouch motors. Reproduced with permission.[117] Copyright 2015, Mary Ann Liebert. f) Hydraulically actuated hydrogels. Reproduced under the terms of the CC BY license.[75] Copyright 2017, The Authors, published by Springer Nature. g) Self-healing polymers. Reproduced with permission.[127] Copyright 2017, AAAS. h) Chameleon's tongue inspired bladder.[131] Reproduced with permission. Copyright Festo AG & Co. KG. i) Microtentacle. Reproduced under the terms of the CC BY license.[138] Copyright 2015, The Authors, published by Springer Nature.

hand mimicking the anatomy of the human one, combining the actuators with ligaments and a rigid skeleton. Following a different approach, researchers at Festo presented a gripper composed by a vacuum-actuated elastomeric bladder, inspired by the chameleon's tongue (Figure 5h).[131] This gripper proved simple handling of objects with wide range of shapes and sizes. A similar grasping device was also developed, which is specialized for delicate objects.[132]

The last categories of FEAs gripper that we discuss here are tentacles, whose grasping strategy consists in wrapping around the object, as would an elephant trunk. Walker et al.[133] demonstrated handling of an object with a 120 cm long manipulator, which consisted of 12 McKibben actuators. Udupa et al.[134] developed asymmetric tube-like pneumatic tentacles made in nitrile rubber. Their four-fingered hand grabbed a bottle and a cup. Martinez et al reported a single soft tentacle able to hold flowers and to wrap around and lift a metallic wrench.[135] A large manipulator inspired by the octopus used McKibben actuators and showed the holding of a basketball.[136] Another manipulator using multiple FEAs demonstrated planar manipulation.[137]

FEAs have been scaled down successfully by several groups: Paek et al.[138] developed the microtentacle shown in Figure 5i, with an inner diameter of 100 μm, small enough to wrap around an ant. It can exert a force of 0.78 mN with a pressure of 60–70 kPa. Russo et al. developed a millimeter-scale articulated arm that is fluidically actuated for tissue handling.[139]

One potential challenge of FEA grippers consists in the use of external pumps and compressors to generate the compressed fluid that drives the actuators. Such components are often bulky and heavy and can compromise the portability of the devices. Preliminary attempts to integrate and miniaturize the generation of compressed fluids showed promising results.[111,140–142] Response time can constitute an additional challenge, since reaching frequencies higher than 1 Hz can be difficult to achieve given the fluidic impedance of the channels and required flow rates for full actuation.

Grippers using FEAs represent one of the most mature technologies among soft grippers, such that the technology has been already spun off in industrial companies,[143,144] and also used for educational purpose.[145] However, most of the existing grippers manipulate only centimeter-size objects and have limited or more often simply no sensing. A potential expansion of this technology consists in its scaling for the manipulation of objects with different sizes and in the integration of advanced distributed sensing. Additionally, the development of integrated soft transducers for the generation of the compressed fluid can further enhance the portability and miniaturization of FEAs grippers, expanding their application fields.

3.3. Electroactive Polymers

Polymers that reversibly deform in response to electric stimuli are called electroactive polymers (EAPs). DEAs[146,147] and IPMCs[148] are the two most widespread EAPs technologies, employed in various fields, including robotics.[149–153] In this section we discuss grippers based on DEAs and IPMCs, while devices based on other types of EAPs and active materials are discussed in Section 3.5.

3.3.1. Dielectric Elastomer Actuators

DEAs are composed of a thin elastomer membrane (thickness 3–500 µm[144,151,154]) sandwiched between two compliant electrodes (Figure 3d). Electromechanical actuation is obtained by applying a high voltage (typically several kV) across the electrodes, which generates an electrostatic attraction (known as Maxwell stress) between them, squeezing the elastomer membrane, resulting in elastomer thickness reduction and area expansion. DEAs are typically composed of soft elastomers (≈1 MPa elastic modulus), can generate large actuation strokes (more than 1000% strain in area expansion[155] has been reported, though 10% to 50% is more typical for long-term operation), fast response time (less than 200 µs[156]), and self-sensing capability.[157,158] Additionally, their electromechanical efficiency can theoretically reach 90%.[159] Thanks to the simplicity of their working principle, DEAs have been shaped into numerous actuator configurations, applied to diverse devices and robots.[160] The large actuation stroke of DEAs corresponds to a low generated stress; therefore multilayer stacking is required when high output forces are demanded, resulting in a more complicated fabrication process.[161,162] The use of high voltage can induce the risk of electric discharges outside the actuator. However, DEAs require very small currents, far below the human-safe threshold. Researchers demonstrated that DEAs can work even in conductive fluids with the proper electrical insulation, consisting for example in additional silicone layers.[163–165] The commercial availability of miniaturized high voltage components, and the recent development of kV thin-film transistors[166] enabled self-contained, mobile DEA robots,[164,167] paving the way for compact systems with embedded high-voltage switching.[166]

The use of DEAs for grasping was first demonstrated with a configuration called self-organized dielectric elastomer minimum energy structures (DEMESs).[168] This configuration consists of a prestretched DEA attached to a flat flexible frame. With no voltage applied, the equilibrium of the entire structure results in a bent shape where the internal stress of the DEA and the bending moment of the frame balance each other. Applying a voltage releases the internal stress and unfolds the actuator structure. This configuration enables out-of-plane actuation using DEAs. **Figure 6**a illustrates the operation principle of a DEMES gripper developed by Kofod et al.[169] Applying a voltage opens the gripper's fingers, and removing the voltage closes them, providing sufficient grasping force to lift up the object. This device uses a single set of electrodes, but it is also possible to segment them to, for example, building longer fingers.[170] Figure 6b is an example of grippers using multisegmented DEMES.[171] The 103 mm long fingers are made of acrylic elastomer as DEA part and polyimide and polyvinyl chloride as frame part. Unlike the previous example, this device developed by Lau et al. exploits unfolding of the actuators to perform pinching grasping, exhibiting the handling of highly deformable objects, here an egg yolk. Meanwhile, other DEA configurations were also applied in grasping. One representative device shown in Figure 6c combines DEAs with stiff fibers.[172] Arranging alignment and rigidity of the fibers constrains in-plane deformation of DEAs, generating various out-of-plane shapes as a consequence of the electrostatic actuation. In Figure 6c, the actuator exhibits wrapping movement capable of adapting to different objects (a cylinder and a grape in the figure) while producing sufficient holding force.

Future developments on DEA-based soft grippers need to overcome the low generated stress. Other than multilayer stacking,

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Figure 6. Soft grippers using dielectric elastomer actuators (DEAs) and ionic-polymer–metal composites (IPMCs). a) Dielectric elastomer minimum energy structure (DEMES). Reproduced with permission.[169] Copyright 2007, AIP. b) Segmented DEMES. Reproduced with permission.[171] Copyright 2017, AIP. c) DEA with stiff fibers.[172] d) IPMC fingers.[186] Reproduced with permission. Copyright Yoseph Bar-Cohen. e) Micro-IPMC fingers. Adapted with permission.[187] Copyright 2008, Springer Nature.

recent researches have demonstrated promising approaches to compensate the low grasping force. One is to incorporate a variable stiffness functionality to improve the holding force, through electrostatic chuckling[173] or rigidity tunable materials.[174] Another approach consists in the implementation of controllable adhesion that provides shear holding force.[175] DEA-based soft grippers including the use of variable stiffness and adhesion are further discussed in Sections 4.2 and 5.1, respectively.

3.3.2. Ionic Polymer-Metal Composites

IPMCs consist of an electrolyte-swollen polymer membrane (thickness typically 100–300 μm) sandwiched between two thin metallic layers. The working mechanism of IPMCs is illustrated in Figure 3e. With no voltage applied, the anions and cations in the electrolyte in the polymer are uniformly distributed. When a voltage bias is applied to the electrodes, the cations migrate toward the cathode, and the anions toward the anode. This leads to differential swelling, causing a bending deformation of the entire structure toward the positive side.[181] Depending on the applied polarity, the device can thus bend in both directions.

The stiffness of IPMCs varies from 0.6 to 21 GPa,[176,177] depending on the materials used for the polymer membrane and the electrodes. This actuator technology provides large bending strokes with low actuation voltages (1–5 V). The use of electrolytes often requires the actuators to be submerged in aqueous solutions, but encapsulation enables operation in

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dry environments[178,179] Similar to DEAs, IPMCs are capable of self-sensing.[180] However, their response speed is slow (e.g., 0.5 and 3.5 min to achieve 50° and 270° of bending angle, respectively[181,182]) and exhibit hysteresis. Moreover, the output stress and efficiency are low.

The bending actuation nature of IPMCs have inspired researchers to exploit them in fingered grippers.[183–186] An example is shown in Figure 6d,[186] where an object with 10.3 g mass is lifted up by a gripper with four fingers. An advantage of IPMCs is that they can easily be manufactured at millimeter size. Deole et al. and Lumia and Shahinpoor developed microgrippers composed of two IPMC actuators (dimensions 5 mm × 1 mm × 0.2 mm),[187,188] manipulating a metallic ball with a mass of 15 mg (Figure 6e). In addition, Jain et al.[189] investigated the behavior of a two-fingered microgripper.

Compared to those of DEAs, recent developments on IPMC-based grippers are rather limited, perhaps due to drawbacks such as slow actuator response and low produced stress. One potential way of pushing this technology toward grasping applications is to exploit its ability to work in aqueous environments. Such applications could include sample return in sea exploration,[84] and drug delivery and surgical manipulation in body fluid.[190]

3.4. Shape Memory Materials

Some polymers and alloys present a shape memory effect: in response to a stimulus (which is often thermal), the material returns from a temporary deformed shape to an initial shape. Representative materials are SMPs and SMAs.[191–194] These materials have been employed in numerous applications across automotive, aerospace, and biomedical field as well as robotics. A summary of the technologies and details of their applications can be found in review articles.[195–197]

SMPs consist of a polymer network composed of elastic domains and transition domains. Heating above the transition temperature causes the transition domain to soften, allowing the deformation of the elastic domain in response to an external force. After cooling, the transition domain stiffens and blocks the deformation of the elastic domain. Heating the material again releases the elastic domain and the device recovers its original, undeformed, state (Figure 3g). In SMPs, the transition occurs due to phase change of the material, where crystallization-melting or vitrification-glass takes a role. SMPs are often employed as composites with other materials to improve their mechanical properties (strength, recovery stress, etc.), and to enable other stimuli effects such as electroactive effect and magnetic-active effect.[198]

SMAs exhibit a shape memory effect due to crystallographic change of the alloy between martensite phase and austenite phase induced by temperature. At low temperature, the alloy is in martensitic form with lower modulus, and can be plastically deformed by an external stress. Heating above the transition temperature transforms the alloy into austenitic form with higher modulus, leading to recovery of the shape to its original undeformed state (Figure 3f). SMAs can also be used as actuators by exploiting the up to 5% contraction upon heating from martensite to austenite phases (this will be discussed later in this article)

Both SMPs and SMAs show stiffness change via phase transition, which can be exploited to use them as variable stiffness components. The use of SMPs as main actuation elements in soft grippers is rare, only little work has been reported.[199,200] This is probably due to their low recovery stress (1–3 MPa[195]) and the fact that they usually need external heaters. SMPs are rather used as variable stiffness components in combination with other active elements, as discussed in Section 4.4. An exception is the device demonstrated by Behl et al.(**Figure 7**a), consisting of a four-fingered gripper using a reversible bidirectional SMP, which has demonstrated pick and place of a coin.[199] Another work presented by Ge et al.[200] showed a 3D printed SMP microgripper (Figure 7b). The gripper, which has fingers of a few mm in length, is capable of picking up a screw when exploiting the shape recovery.[200] In the rest of this section, we focus our discussion on SMAs.

SMAs exhibit high active stress (on the order of several hundreds of MPa), with substantial strains up to 5%.[201] Nickel titanium is the most commonly used alloy for this type of technology. SMAs have a high elastic modulus (10–83 GPa below transition temperature, and 0.1–41 GPa above transition temperature[195,202,203]). However, SMAs can be formed into coiled springs with a wire diameter of 25–500 μm, exhibiting compliance and large actuation strain (e.g., 50% linear contraction[204]). The conductivity of the alloys enables direct Joule heating through the material, producing thermal activation intrinsically, without the need for an external heater. SMAs can also be used as strain sensors by monitoring the change in resistivity.[205,206] The response speed is relatively slow (≈3 Hz[195]), and they present hysteresis in actuation cycles. SMAs can be driven by low voltage, but they require high currents and have low efficiency.

One approach to building SMA-based adaptive grippers consists in combining them with flexible beams and hinges.[207–209] Simone et al.[70] developed a prosthetic gripper made of 3D printed tendon-driven structures mimicking the shape of the human hand. The device has three fingers that can be actuated independently enabling grasping and holding a coffee cup, a screwdriver, a pencil, and a rectangular box.

Another recently developed approach is the integration of SMAs and compliant materials (e.g., silicone elastomers) that provide improved adaptability to the object.[69,210–214] She et al.[214] developed a robotic hand shown in Figure 7c, where every finger is composed of SMA strips and a silicone rubber structure. Shape recovery of the strips toward programmed curved shape realizes the finger motion. The robotic hand displayed adaptability and dexterity resulting in the grasping of various objects, from a wire spool to a thin card. Another example of a robotic hand based on the same technology is presented in Figure 7d; the device is composed by SMA wires encapsulated in an elastomeric articulated structure with a glass fiber sheet.[69] The SMA wires contract when heat is applied to them, resulting in bending motion of the fingers, in the same manner of tendon-driven actuation (see Section 3.1.2). This device has grasped different objects, such as a light bulb, a mouse, a pair of scissors, and a ball of crumpled paper. An advantageous feature of SMAs is their easy miniaturization. SMA microgrippers have been developed based on rigid materials and flexural

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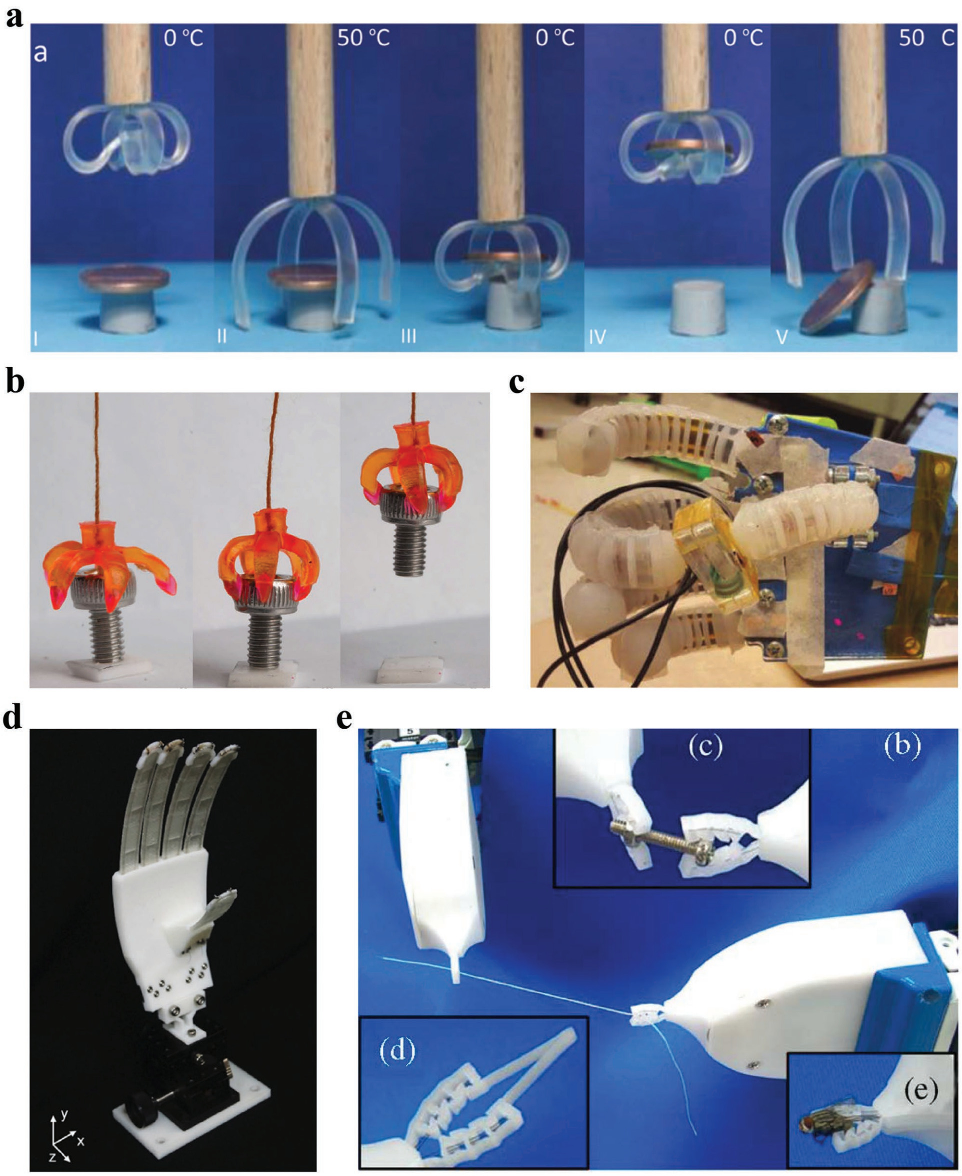

Figure 7. Soft grippers using actuation of shape memory materials. a) Bidirectional shape memory polymers (SMPs).[199] b) 3D printed SMP structure. Reproduced under the terms of the CC BY license.[200] Copyright 2016, The Authors, published by Springer Nature. c) Shape memory alloys (SMAs) with elastomeric finger structure. Reproduced with permission.[214] Copyright 2016, Mary Ann Liebert. d) Articulated elastomeric structure with SMA wires. Reproduced with permission.[69] Copyright 2016, Elsevier. e) SMA microfingers. Reproduced with permission.[219] Copyright 2010, IEEE.

joints.[215–217] Softness in such devices can be increased by the using superelastic SMAs[218] or compliant materials,[219] or by decreasing the thickness of the structure.[220] Figure 7e shows a soft microgripper developed by Lan et al.[219] that has two fingers (10 mm length), consisting in SMA wires and a polyoxymethylene flexible frame. Each finger is equipped with self-sensing through the measurement of the resistance change of the SMA wire. The gripper demonstrated manipulation of a string and screws (diameter 1.7–4 mm), as well as holding a fly.

Future work on grippers based on shape memory materials could address shape recovery (actuation) speed and hysteresis. Speed is dominate by the cooling time constant, which can be decreased by scaling down the actuator.[221] Larger actuators therefore would require additional cooling elements such as circulating water or electrocaloric systems.[222] For SMPs, it has been reported that blending of carbon nanofibers improves the recovery speed.[223,224] Hysteresis can be lowered in SMAs by magnetization.[225] Similarly, in SMPs, it has been reported that polymers composed of poly(vinyl chloride) and polyesterurethanes show reduction of hysteresis during shape recovery.[193,226]

3.5. Other Active Materials

When developing stimuli-responsive polymers and gels, researchers often demonstrate soft grippers as a potential application. Such materials have shown grasping in response to the application of various external stimuli including chemical

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(pH change,[227–229] salt concentration,[230] and solvent exposure[231]), dissolution,[232] humidity change,[233] electrical,[234,235] thermal,[236–242] optical,[235,243,244] and magnetic.[245–247] Those stimuli triggered actuators exploit swelling, ion migration, oxidation, thermal expansion, phase transition, and field deformations. For more details on stimuli-responsive soft actuation, a recent review is available.[248]

A promising application of such stimuli-responsive materials are microgrippers for assembly of micro-objects, surgery, and drug delivery.[190] **Figure 8**a top shows schematics of a microgripper developed by Ongaro et al.,[236] consisting of folding arms that can be actuated by thermal stimulus on a hydrogel (*N*-isopropylacrylamide-*co*-acrylic acid) integrated with a stiff frame (SU-8 polymer). The gripper has diameters of 4 and 0.8 mm in the flat and folded states, respectively. By doping of the gel with magnetic nanoparticles, the gripper can be remotely displaced by an external magnetic field. Figure 8a bottom shows pick and place operation of the gripper, where the temperature change of the surrounding fluid induces a phase transition with associated swelling and shrinkage of the hydrogel, resulting in reversible open-close motions of the folding arms. The external magnetic field controls the positioning of the device. Diller and Sitti[245] instead used the external magnetic field also to induce the gripping action of their microgrippers, as shown in Figure 8b. The devices presented are made of a polymer filled with a magnetic powder. The jaws of the grippers are magnetized in opposite directions, generating reversible open-close movements according to the applied field. With this operation, manipulation of 200 μm microspheres and of a several mm diameter rod were demonstrated. An interesting microgripper is shown in Figure 8c, which works by stimulation with infrared (IR) light.[244] The grippers' fingers (≈10 mm length) are made of a polystyrene sheet patterned with a black ink. Absorption of the light by the ink surface results in localized heating that induces shrinkage of the structure when the

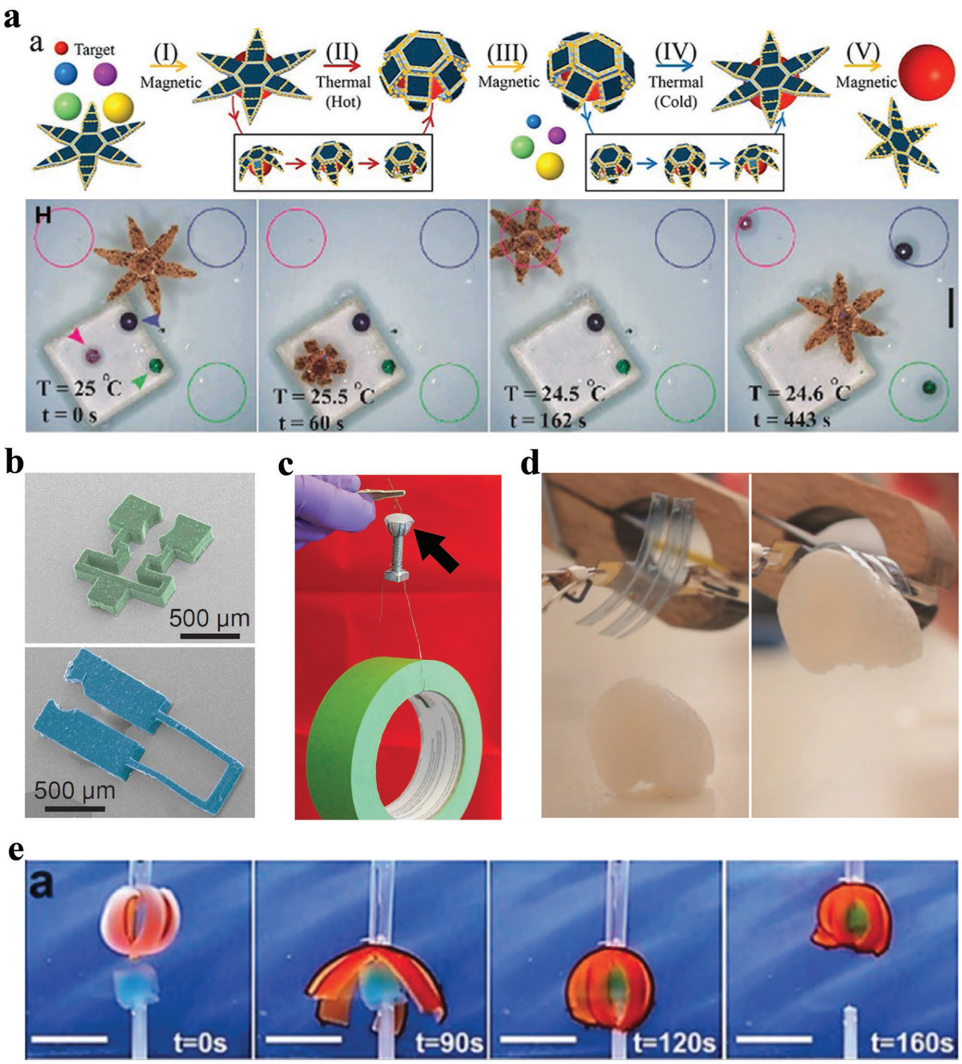

Figure 8. Soft grippers using other active materials. a) Thermally-responsive hydrogel. Reproduced with permission.[236] Copyright 2016, The Authors, published by Springer Nature. b) Magnetic polymer.[245] c) Light-responsive polymer. Reproduced with permission.[244] Copyright 2017, RSC. d) Humidity-responsive polymer.[233] e) Bio-hydrogel (chitosan and cellulose/carboxymethylcellulose). Reproduced with permission.[229] Copyright 2017, RSC.

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temperature exceeds the activation temperature. The device is able to hold ≈925 × its own weight. Alici and Huynh.[249] demonstrated microgripping using a type of electroactive polymer[250]: their two-fingered gripper showed the lifting up of an object weighing 8 mg.

Swelling is a major type of actuation that can be stimulated by various means. Taccola et al.[233] developed a soft gripper that exploits the water swelling nature of PEDOT:PSS (poly(3,4-ethylenedioxythiophene) polystyrene sulfonate) for humidity stimulated actuation (Figure 8d). The conductivity of PEDOT:PSS allows the Joule heating of the material to control the amount of swelled water contents by evaporation, enabling reversible grasping actuation. Another example of swelling gripper presented by Duan et al.[229] is made of biohydrogel (chitosan and cellulose/carboxymethylcellulose)(Figure 8e). In aqueous solution of 0.1 M HCl, the fingers are actuated by pH-triggered swelling, achieving the lifting of a hydrogel cube weighing 5 g.

Combining materials with different thermal expansion coefficients, heating can produce out-of-plane actuation as a consequence of thermal expansion. Yao et al. showed a grasping device composed of a PDMS layer and a heater membrane made of silver nanowires.[238] Upon heating, the expansion of the PDMS layer produced bending of the fingers' structure, enabling the handling of an object. Similarly, Zhou et al.[242] demonstrated grasping of crab's egg with ≈1 mm diameter, using microthermal actuators made of a platinum heater and parylene covering layers.

Research in the use of stimuli-response materials for gripping is not as mature as the gripping methods described earlier in this paper. However, investigation of grasping based on new stimuli could lead to grippers that can react to chemical properties and photo/thermal energies of the object or the environment without the need of additional sensing. Such systems are expected to expand the application fields and working environments.

4. Gripping by Controlled Stiffness

Grippers based on variable stiffness materials and structures use a different mechanism respect to the gripping by actuation presented in Section 3. The general method consists of setting the gripper's structure in its "soft" configuration, approaching and enveloping the object to be grasped, and finally stiffening the structure to hold it through caging. This method can result in high holding forces with a minimal compression applied to the object. Moreover, the grasping strategies can be expanded through the use of local stiffening of the structure, enabling multiple degree-of-freedom shape change with a single actuation input. In this section, we review and discuss variable stiffness technologies used in soft grippers, such as granular jamming, low-melting point alloys, electrorheological and magnetorheological fluids, and shape memory materials. For other stiffness tunable materials such as thermoplastics,[92,251,252] a review on variable stiffness technologies for soft robotics is available.[253] Tendon-driven is also able to achieve variable stiffness through antagonistic configurations.[254] However, since little work has been done with soft materials, we focus on the others technologies listed above.[255,256]

4.1. Granular Jamming

A vacuum-sealed package of ground coffee beans is hard, but becomes soft as soon as it is opened. The mechanism underlying this phenomenon is called granular jamming or granular transition. The change in stiffness is a consequence of the change of pressure between the granules:[257] the depressurization of a loose granule-filled bag produces compressive forces between the granules, which constrain their physical movements, making the whole bag behave as one solid object. Injection of air into the bag returns it to a soft state: the granules free to move, with a liquid-like behavior. Ground coffee is the most widely used type of granules, but the following have also been reported: glass, plastic, metallic beads and beans.[258,259] Jamming actuators feature simple structure and stiffness control by means of pressure. Stiffness change achievable with this technology is reported to be up to 24 times.[260] The rate of stiffness change is rather fast; 0.1–1.1 s to solidify, and 0.1–1 s to liquefy.[261,262] Transition time generally depends on the pressure difference and flow rate provided by the pump, and the volume of granule-filled bag. The need for a pump generating a relatively high pressure difference is a limitation when portability is required. Nevertheless, in robotics, granular jamming has been demonstrated in mobile robots as well as in manipulators.[263–267]

After its shape adaptive grasping capability was demonstrated in its early development by Rienmüller et al. in 1988 (Figure 1),[268] granular jamming was shown to enable high performance in soft grippers. One representative example is the device called the "universal soft gripper" developed by Brown et al.,[269] shown in **Figure 9**a. The high compliance of the ground coffee-filled bag adapts to the object, and evacuation of air provides sufficient rigidity to hold and lift it up. This gripper successfully handled objects with highly diverse shapes, such as small flashlight bulbs, small plastic bags, LEDs, bottle caps, plastic tubing, foam ear plugs, and a variety of hardware items and office supplies in addition to the objects shown in Figure 9b. The device cannot grasp flat objects, as it cannot envelop and cage them. Granular jamming may not be a good match for handling deformable objects, because it is almost impossible to conform to the object deformations after the gripper structure has been solidified. The universal jamming gripper has been applied to industrial environment,[262] and several research applications have been demonstrated, such as in prosthetic,[270] assembly tasks,[271] and human-robot cooperation,[272] as well as integration with learning algorithms.[273] Licht et al.[274] employed jamming gripper as an end effector of a remotely operated vehicle for deep sea sampling, and showed that the gripper was able to generate over 35 N of pulling force on a sample (stainless steel rod) at a depth of 1200 m (Figure 9c). When multiple granule-filled bags are used as end effectors, granular jamming shows improved versatility to deal with an even larger variety of objects. Figure 9d presents a two-fingered robotic hand developed by Amend and Lipson,[275] where each finger is equipped with a granular jamming bag.

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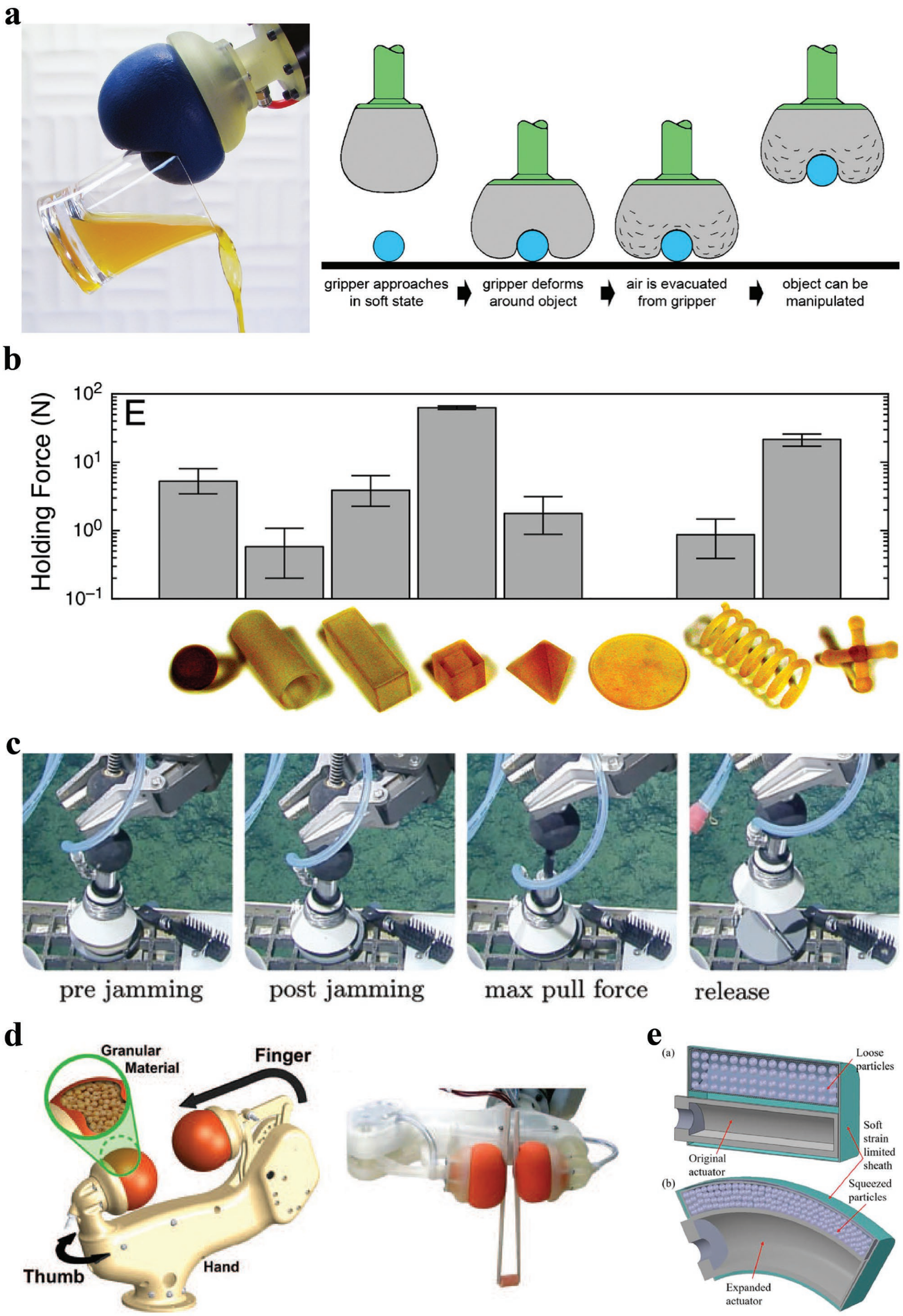

Figure 9. Soft grippers using granular jamming. a) Representative configuration, its working mechanism, and b) Holding force for different types of object geometry. Reproduced with permission.[269] Copyright 2010, National Academy of Sciences. Image top left: reproduced with permission, copyright 2010, John Amend. c) Holding force test in deep sea (1200 m depth). Reproduced with permission.[274] Copyright 2017, Mary Ann Liebert. d) Two-fingered configuration. Reproduced with permission.[275] Copyright 2017, Mary Ann Liebert. e) Combination with fluidic elastomer actuator. Reproduced with permission.[88] Copyright 2017, IEEE.

They showed that this configuration features high dexterity to, for example, handle chopsticks to manipulate small objects.

As a variable stiffness element, granular jamming can also be combined with other actuation technologies into soft grippers. Li et al.[88] integrated a jamming component into a fluidic elastomer actuator (Figure 9e). The bending deformation of the actuator elongates and squeezes the jamming part. This confines granules inside, realizing passive stiffening without the need for vacuum. In a similar work, the jamming part is actively controlled and is independent from the fluidic

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elastomer actuator.[93] Since both granular jamming and pneumatic actuators are based on pressure difference, their combination is advantageous since the pressure-generating device can be shared, increasing the global dexterity while avoiding the increase in complexity of the system. Fujita et al.[276] used a linear actuator to adjust the inner volume of the granular bag to increase adaptability to object. Combining jamming with tendon-driven actuation, Cheng et al.[265] developed a manipulator with four segmented sections. The device showed holding of a heavy object, as well as dexterous manipulation of a cup.

Future research regarding granular jamming could address for further increasing versatility on object types. For example, jamming grippers could be equipped with an adhesion technology to enable handling flat and deformable objects that are currently difficult to handle. Another potential approach is to modify geometry of the granular-filled elastic bag, as can be seen in the literature.[277] Layer jamming, a variable stiffness technology that relies on friction between overlapping layers,[278,279] is a promising technology for future applications due to its low thickness structure, leading to lightweight fingered grippers with variable stiffness.

4.2. Low-Melting Point Alloys

LMPAs, also known as Field's metal or Fusible alloys, change their phase from solid to liquid in response to heat. This phase change can be exploited to obtain variable stiffness structures, once the alloys are encapsulated in soft structures made of elastomers and foams.[280–283] Reported relative stiffness changes are ranging from 25 to over 9000 times.[284–286] In these components, heat is applied externally by integrating a heating element, or directly by Joule heating by running current through the alloy. Melting temperature of the alloys is typically 47–62 °C. In the solid state, their Young's modulus is 3–9 GPa, which determines the maximum theoretical stiffness achievable. An example of LMPA variable stiffness element is shown in **Figure 10**a. This element consists of an LMPA track embedded in elastomer matrix. Applying electric current to the track heats it, and the entire structure goes from rigid to soft.

LMPAs were first used as adaptive grasping in a four-fingered metamorphic robot able to grip and hold a 120 mm diameter ball and a block (Figure 1).[280] This robot, developed by Nakai et al.(Figure 1), in which every finger is moved externally by servomotors, consists of a silicone elastomer matrix encapsulating an LMPA and a heater made of a conductive fabric. There is also a temperature sensor integrated in the same structure. The stiffening effect enabled the robot to climb up a ladder, by exploiting both its soft and rigid states. Another example is a two-fingered soft gripper shown in Figure 10b.[174] Each finger consists of an silicone structure containing an embedded LMPA track and a prestretched DEA (Figure 10c). The bending part of the finger is 35 mm long, and weighs ≈1 g. The LMPA track is conductive and can be Joule-heated. When the LMPA is in liquid phase, the whole structure is in its soft state, and the electrostatic actuation from the DEAs moves the fingers from the bent shape to a flat shape. Solidifying the LMPA (by removing the heating current) while keeping the DEAs actuated results in a desired rigid shape of the fingers, and the DEA can be turned off. With this operating procedure, the gripper has successfully picked up a plastic dish filled with metal washers with a mass of 11 g (5.5 times its own weight) using an extremely small active grasping force of 0.24 g, clearly exploiting the variable stiffness effect given from the LMPA. A similar device, displayed in Figure 10d,e, consists of an LMPA track encapsulated elastomer structure combined with a fluidic elastomer actuator.[91] In that work, the variable stiffness actuator is integrated in a three-fingered gripper capable of lifting up an object with a mass of 780 g, much heavier than the device itself.

For further developments, a challenge is to decrease the phase transition time of LMPAs. Depending on size and geometry, reported melting time for LMPAs ranged from 1 to 30 s, while solidifying (cooling) time takes over 60 s.[174,286] Although melting time can be made decreased by increasing electric input power, solidifying time is limited by the thermal conductivity of the encapsulating elastomer and heat transfer between the surface of the device and the surrounding air. The slow response can be an issue when quick manipulation of multiple objects is required. Potential solutions involve the use of soft materials with high thermal conductivity (e.g., refs. [287,288]) for the substrate encapsulating LMPAs, or the integration of an additional cooling element based on, for instance, the electrocaloric effect[222] or circulating water. Surface patterning to increase the exposed area[289] and fractal channel design[290] can be a further method to decrease the cooling time.

4.3. Electrorheological Fluid and Magnetorheological Fluids

When exposed to electromagnetic fields, some fluids increase their apparent viscosity until reaching a viscoelastic behavior. When encapsulated in an elastic structure, such a change in viscosity leads to a mechanical stiffness change of the entire structure. There are two types of field-responsive fluids: ER fluids and MR fluids. ER fluids consist of polarizable particles (size 0.1–100 µm) suspended in a dielectric fluid such as an oil.[291] Under an electric field (typically up to 5 kV mm^{-1}), the particles develop fibrillated chains in the direction of the electrical flux lines, due to the dielectric polarization and the oriented polarization of molecular dipoles.[292] The fibrillated chains resist the deformation of the fluid domain, leading to increased stiffness of the structure. Similarly, in response to a magnetic field, MR fluids forms chains of ferromagnetic particles (size 3–5 µm) by magnetization, along the magnetic flux lines.[293] In MR fluids, oil is often used as fluidic media. Typically, magnetic fields of up to 500 mT are applied to obtain a viscoelastic behavior. The response time of ER/MR fluids is relatively short, less than 10 ms.[292] Their relative stiffness change ranges from a few times to a few tens of times,[294–297] and generally MR fluids have shown greater changes than ER fluids.[298,299] ER fluids have generally lower energy consumption power requirements, because the generation of electric fields relies only on applying an electrical potential (with no steady state current flow), while magnetic fields are proportional to electric current. In addition, ER/MR particles can also be mixed into foams and elastomers, but the obtained stiffness change is greatly reduced with respect to their use in fluids.[300,301] ER/MR fluids are

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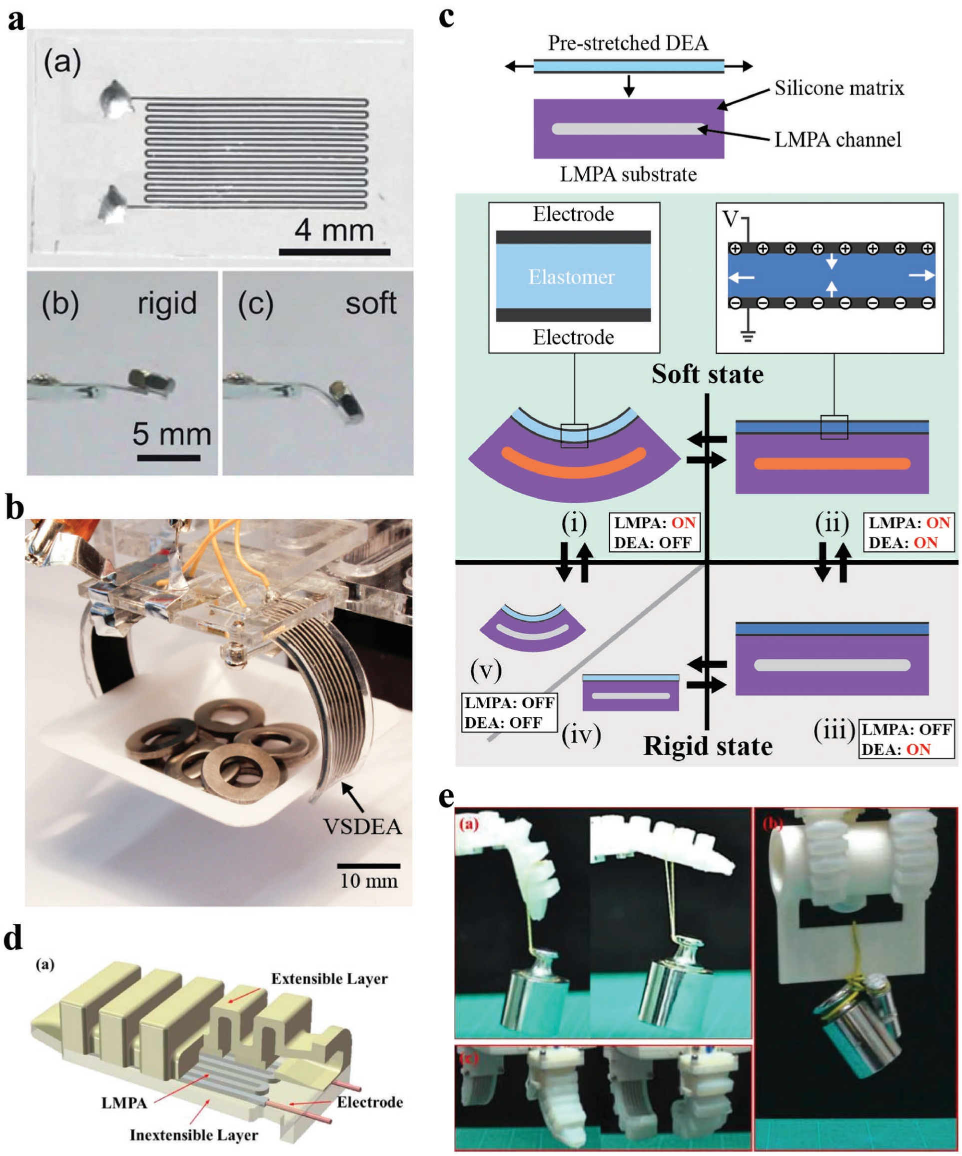

Figure 10. Soft grippers using low-melting point alloys (LMPAs). a) An LMPA variable stiffness element.[286] b) Combination with dielectric elastomer actuator (DEA), and c) its structure and operating principle. Reproduced with permission.[174] Copyright 2015, IEEE. d) Combination with fluidic elastomer actuator (FEA), and e) gripping operation. Reproduced with permission.[91] Copyright 2017, IEEE.

traditionally used in dampers, clutches, and valves,[302,303] while they have been also implemented in some robotics applications such as manipulators.[304]

For soft grasping applications, ER fluids were first used in 1989 in a robotic finger covered by conductive elastomeric skin encapsulating the ER fluid over grid of copper electrodes (Figure 1).[305] With no electric field applied, the ER fluid layer acts as a compliant tactile sensor. When the finger touches an object, the layer deforms, thus changing the capacitance measured using the electrodes. After being pushed onto an object, when the ER layer can be solidified by applying a high voltage on the electrodes, and it then interlocks with the object, providing large lifting forces. An ER fluid layer was also combined with an electroadhesive pad in another robotic gripper in 1992 by Monkman (Figure 1).[306] Since both ER fluids and electroadhesion work with high electric fields (i.e., require generally high voltages), the configuration of this adaptive gripper is simple despite the multifunctionality, providing both variable stiffness and electroadhesion since the high voltage connections can be efficiently reused. The use of ER fluids was further extended to micromanipulation.[307] Arai et al. developed a microgripper consisting in a finger with a joint containing an ER fluid; the stiffness of the flexible finger can be changed by controlling the voltage applied to the ER joint.

MR fluids have also been used in gripping applications. Pettersson et al.[308] developed an end effector consisting of two rigid arms, each equipped with an electromagnet and an MR fluid-filled pouch. With no magnetic field applied, the pouch conforms to the object as the arms squeeze. Activating of the electromagnets solidifies the pouches, caging the target that

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can be therefore successfully lifted. This gripper demonstrated handling of various food items, such as, apples, tomatoes, carrots, and strawberries. Nishida et al.[309] also created a similar end-effector composed of an electromagnet and an elastomeric bag filled with a reinforced MR fluid. They demonstrated handling of a plastic container, an eraser, a tape, and small sphere and cube.

The implementation of ER/MR fluids in soft grasping systems is limited except for the early developments discussed above.[305–307] The reason may be due to low absolute stiffness achievable by solidifying the fluids. Reported yield stress is up to 250 kPa,[310–312] which coincides with the low stiffness of the entire structure encapsulating the fluid. Absolute stiffness could be increased by applying higher electric/magnetic fields. However, in MR fluids, higher magnetic fields require higher current, resulting in high energy consumption and heating. For ER fluids, the use of microfabrication processes is a potential approach to increase their stiffness variation, since the intensity of the electric field depends on the gap between the electrodes sandwiching the fluid. It would also be interesting to combine ER/MR fluids with other actuation and adhesion technologies relying on the same field source. For example, ER fluids can be combined with electroadhesion as reviewed above, but also DEAs could be good candidates, since they all require high electric fields.

4.4. Shape Memory Materials

Materials that exhibit shape memory effect, such as SMPs and SMAs change their stiffness through phase transition. In this section, we focus our discussion on their variable stiffness capability, while other properties were covered in Section 3.4. SMPs have generally larger relative stiffness change and lower modulus in both soft and rigid states (0.01–3 GPa below transition temperature, and 0.1–10 MPa above transition temperature, corresponding to 100–300 relative change), compared to SMAs (10–83 GPa below transition temperature, and 0.1–41 GPa above transition temperature, corresponding to 2–10 relative change).[195,202,203] The small relative stiffness change of SMAs encourages their use in soft grippers as actuators rather than variable stiffness components. Therefore, in this section we focus on SMPs. As variable stiffness components, SMPs have been coupled to other soft actuator technologies including FEAs,[86,90,313] SMAs,[314] and DEAs.[315]

Following the initial investigation in the early 1990s using shape memory foams,[109] several variable stiffness soft grippers using SMPs have been developed. Firouzeh and Paik[316] recently presented a gripper that has three tendon-driven fingers with an origami structure (**Figure 11**a). In this configuration, hinges between the origami segments are composed of SMP layers, acting as variable stiffness joints. Control of stiffness relies on a heater made by a metallic mesh embedded in the SMP layer. The stiffness change enables two grasping modes: a stiff mode to exert large forces, and a soft mode to gently handle the object, a sponge in this case. Moreover, the same group showed another gripper with similar tendon-origami configuration, which exhibited independent stiffness control of every SMP joint for achieving various finger shapes,[317] or multiple grasping modes thanks to different origami patterns enabling bending about multiple axes (Figure 11b).[318]

Wang and Ahn[319] demonstrated another approach of SMP-based variable stiffness grasping, shown in Figure 11c. In this case, SMP joints with Ni-chrome wire heaters are embedded in a layered finger (120 mm length) made of polydimethylsiloxane (PDMS) (Figure 11d). The same structure also contains SMA wires providing bending actuation of the finger. Selective activation of different SMP parts enables both high holding force and different grasping postures similar to those displayed by a human hand, realizing handling of delicate objects (a raw egg and a vegetable). It can withstand up to ≈590 g of pulling force when holding a test object with a diameter of 80 mm.

SMPs have demonstrated their usefulness also in DEA-based soft grippers (Figure 11e).[320] This grasping device, developed by McCoul et al., has a layered structure composed by a stretchable circuit, a dielectric elastomer, and a flexible substrate (Figure 11f). The electrodes, made of an SMP-carbon composite, can simultaneously provide electrostatic actuation and variable stiffness by Joule heating. Their gripper was able to hold an object weighing 30 g, 30 times its own weight. The phase transition behavior of SMPs also allows them to be used in multimaterial 3D printing.[321] This approach has been employed to manufacture a soft gripper composed of 3D printed parts with SMP and PLA materials, and elastomer pneumatic actuators.[89,322]

Potential challenge of SMP-based variable stiffness for soft grippers is the transition time, mainly for the cooling phase. Similar to the case of LMPAs discussed in Section 4.2, the grippers rely on heat dissipation primarily through convection around the SMP parts, resulting in slow operation frequency (≈0.05 Hz[316]). Solutions may follow the approaches already discussed for LMPA, such as the use of highly thermally conductive materials, integration of a cooling unit and surface patterning.

5. Gripping by Controlled Adhesion

Adhesion is the interface attraction between two surfaces; it then leads to a shear stress proportional to the generated normal pressure. Soft grippers with integrated adhesion can generate high holding forces thanks to the large shear friction force. At the same time, the closing force normal to the surface of the object is much smaller than when gripping by actuation, allowing the manipulation of very fragile objects. The high ratio between shear force and closing force is a promising feature for lightweight portable grippers, thanks to the high device-to-object mass ratio and low power requirements. Since the adhesion force is normal to the surface of the object, it enables additional strategies for handling, such as single-point grasping, which is impossible for grippers based on active shear force or enveloping. These features improve dexterity and versatility of soft grippers. For example, a flat item is often difficult to handle by fingered systems but is easy to pick up by normal adhesion. Adhesion is also effective for soft, deformable objects, because the interface attraction automatically chases the object deformations when the gripper structure is sufficiently compliant.

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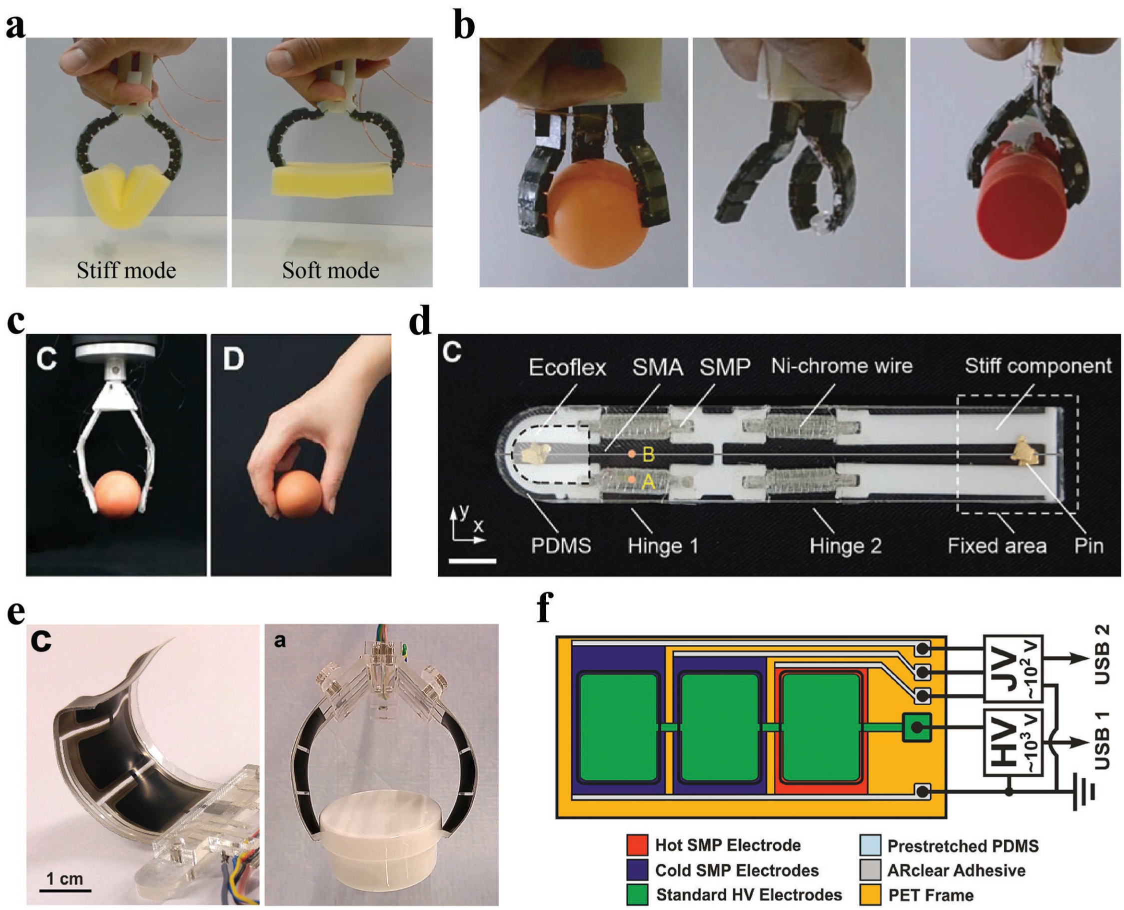

Figure 11. Soft grippers using variable stiffness of shape memory polymers (SMPs). a) Tendon-driven fingers with an origami structure. Reproduced with permission.[316] Copyright 2017, IEEE. b) Tendon-driven fingers with independent joint stiffness control. Reproduced with permission.[318] Copyright 2017, IOP Publishing. c) Combination with SMA wires, and d) its structure. Reproduced with permission.[319] Copyright 2017, Mary Ann Liebert. e) Combination with dielectric elastomer actuators (DEAs), and f) its structure. Reproduced with permission.[320] Copyright 2016, IOP Publishing.

There are two major adhesion technologies used in soft grippers: electroadhesion and what we will call here geckoadhesion. The former relies on electrostatic attraction between surface charges induced by applied electric fields. Inspired by gecko's foot structure, the latter is a synthetic directional adhesive that exploits the strong van der Waals forces between compliant hierarchical microstuctures and the surface of an object.[323] In this section, we focus on these two adhesion strategies, and discuss other related technologies at the end.

5.1. Electroadhesion

The Coulomb force, or electrostatic force, is the attraction between positive and negative electric charges. Electroadhesion exploits this phenomenon by controlling the amount of electric charges on both sides of the interface between the device and the object. An applied electric field, often from interdigitated electrodes covered by a thin passivation layer, leads to polarization charges in dielectric objects and to electrostatic induction on conductive objects. Electroadhesion has been shown to be effective on both smooth and rough surfaces.[306,324] This adhesion technology relies on high electric fields, and thereby generally requires voltages on the order of a few kV. Measured adhesion pressure is up to 13 kPa in the normal direction (on a paper surface, device made of elastomer),[175] and 62 kPa in shear direction (on a glass surface, device made of elastomer).[325] Applications of electroadhesion include wafer handling,[326] wall-climbing robots,[324,327,328] flying robot perching,[329] and rigid grippers.[330] For electroadhesion, it is essential to generate out-of-plane electric fields from the gripper to have high electric fields in the object being grabbed. For this reason, most electroadhesion devices use electrodes with laterally bipolar design, such as coplanar interdigitated and spiral shapes. The performance of electroadhesion can be improved by optimizing the electrode geometry (e.g., gap and width) and the thickness of the insulation layer, as has been suggested in the literature.[325,331,332] Ruffatto et al.[333] demonstrated the combination of electroadhesion with other adhesion technologies, in particular geckoadhesion.

For use in soft grippers, electroadhesion is implemented in association with an actuation unit to deform the gripper, such as electromagnetic motors,[334,335] FEAs (**Figure 12**b),[336] and SMPs.[337] Figure 12a shows an electroadhesion gripper developed by Grabit Inc. The gripper on the left side consists of eight fingers made of flexible-PCBs with interdigitated

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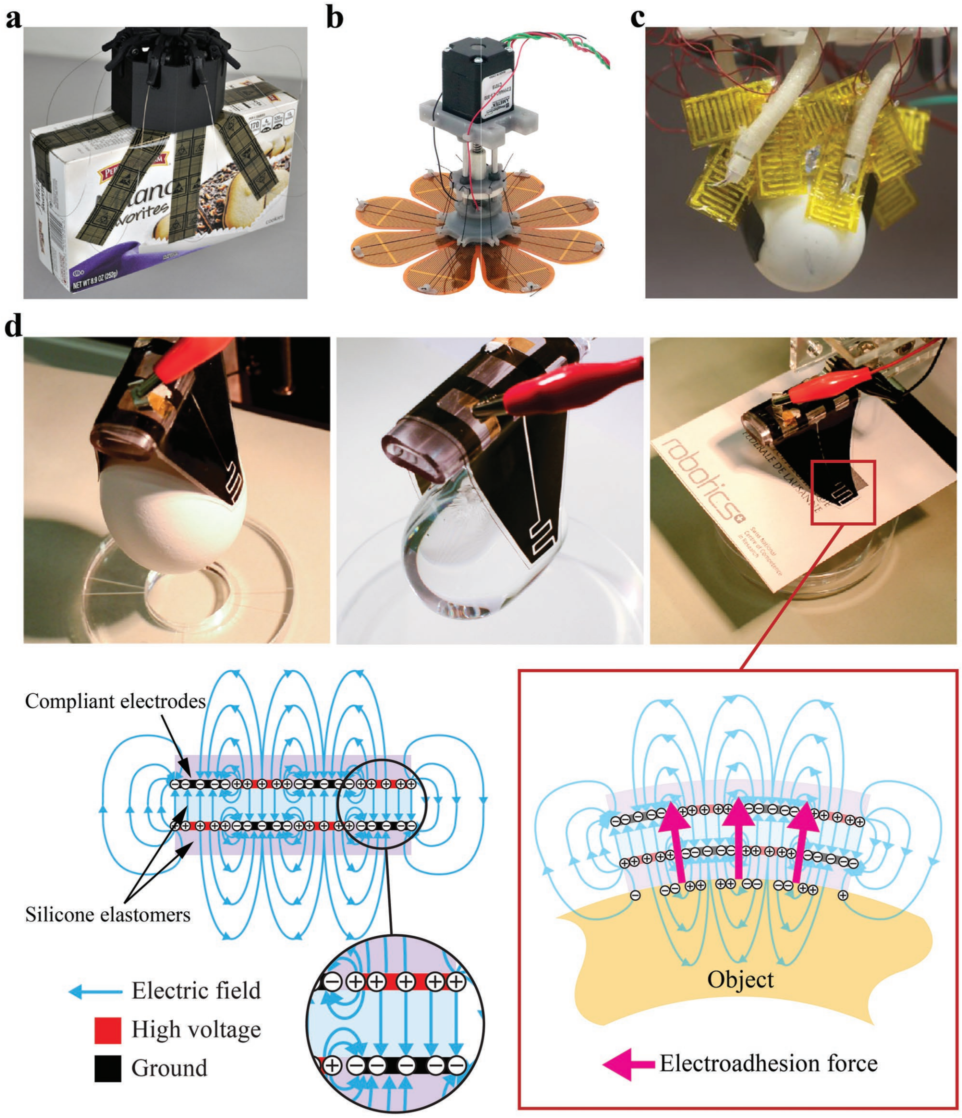

Figure 12. Soft grippers using electro-adhesion. a) Flexible-PCB with external magnetic motors. Reproduced with permission.[334] Copyright Grabit Inc. b) Flexible-PCB with external magnetic motors. Reproduced with permission.[335] Copyright 2017, IEEE. c) Combination with fluidic elastomer actuators (FEAs). Reproduced with permission.[336] Copyright 2016, IEEE. d) Integration with dielectric elastomer actuators (DEAs).[175]

electrode patterns to generating the adhesion. These fingers are moved externally by motors. The device is showed handling a cookie box, an apple, and metallic cans. Moreover, the same company demonstrated the transportation of a package using a flying drone (quadrotor) equipped with a similar gripper. Schaler et al.[335] developed the electroadhesive gripper shown in Figure 12b, and demonstrated handling of a large, flexible metallized PET film. Each finger is 32.5 mm long, and made of a flexible-PCB. Liang et al. employed FEAs to actuate the electroadhesive fingers (30 mm length) made of polyimide and a conductive silver paint, as shown in Figure 12c. In these grippers, the adhesion part consists in a flexible material. An exception is represented by the soft gripper developed by Shintake et al.[175] (Figure 12d), where both electroadhesion and electrostatic actuation are combined in a single stretchable element. In this gripper, the electrodes of the DEA are realized with an interdigitated shape, obtaining finger actuation by thickness reduction and area expansion of the elastomer while forming out-of-plane electric fields; such fields penetrate into the object surface and lead to electroadhesion forces by inducing surface charges on the object. The gripper can handle of a wide range of objects such as a raw egg, a highly deformable water balloon, and a flat piece of paper. Thanks to the hybrid design, the gripper is lightweight (≈1.5 g), and is capable of lifting up weights up to 82.1 g, 54.7 times its own weight. As mentioned in Section 4.3, electroadhesion has also been combined with ER fluids to improve object holding performance, thanks to the stiffness change provided from the ER fluid.[306]

A potential challenge for soft grippers using electroadhesion is the small hysteresis in the adhesion force due residual charges that remains after turning off the applied voltage. The residual force is low and can lasts several seconds for dielectric

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objects.[338] It has been reported that bare electrodes reduce the residual forces for this type of material.[339] For conductive objects, an effective solution is to use AC voltage instead of DC.[326] The surface conditions (e.g., the presence of dust and moisture on at the interface between the gripper and object) also affect the performance of electroadhesion and can lead to a reduced holding force. A potential solution to this problem is to implement self-cleaning.[340]

5.2. Geckoadhesion (Dry Adhesion)

Geckos are able to climb surfaces thanks to microfibers on their bottom foot surface which attract the object surface by the van der Waals force, resulting in generation of shear force. Geckoadhesion is inspired by the microfibers of geckos.[341–343] The adhesion is activated by pressing the microfibers against the object surface in the direction normal to the surface (preloading), and deactivated by removing the preloading force. By setting the angle of the fibers, it is also possible to realize directional shear adhesion force.[344] Geckoadhesive works on both smooth and rough surfaces, but it has difficulty in adhering to low surface-energy materials.[345] Self-cleaning is unique feature in this type of adhesion technology.[346,347] It has been also shown that surface coating, in particular with poly(dopamine methacrylamide-*co*-methoxyethyl acrylate), allows geckoinspired pillars to adhere on wet surfaces.[348] Reported adhesion pressure is up to 23.5 kPa in normal direction, and 120 kPa in shear direction.[343,349,350] Previously developed applications using geckoadhesion include wall climbing robots,[344,351] human surface climbing device,[352] perching mechanism for flying robots,[353] and object manipulation in space.[354]

Geckoadhesion has been implemented in soft grippers where a passive mechanism enables both activation and deactivation of the microfibers arranged on a flexible film substrate (**Figure 13**a).[355–357] When the object is touched, the passive mechanism conforms the film and preloads the microfibers. Releasing can be done simply by pressing the gripper to the object. These grippers showed handling of various objects with curved surfaces such as a basketball, rolls, a water bottle, a coffee cup, an apple, a large plastic container, and a water-filled, deformable plastic bag, as well as a flat glass plate. The gripper was able to lift 4.3 kg, even though its weight was only 0.015 kg, corresponding to 286.7 times its own weight. Geckoadhesion has also been combined with actuation elements. Figure 13b shows an inflatable membrane gripper covered with geckoinspired, mushroom-shaped microfibers.[95] Inflation of the membrane controls the contact area, enabling both picking and releasing of the object. Thanks to the large membrane area, the gripper has demonstrated simultaneous transfer of steel balls of different size. A similar research has been performed by Song et al.,[358] where an elastomer membrane with mushroom-shaped microfibers has exhibited holding of various objects as shown in Figure 13c: a rounded glass flask, a coffee cup, a pair of cherry tomatoes, and a plastic bag. In this system, adhesion is controlled by the internal pressure of the elastomer membrane, and the loading force normal to the interface. Another approach has shown a multifingered gripper where each finger is made of a liquid crystal polymer (LCP), with a geckoadhesive pad placed on the fingertip.[359] The adhesion of the pads to the object is obtained through magnetic force established between an external electromagnet and small magnets placed on each finger, while the thermal actuation of the LCP fingers produces their bending, resulting in the peeling-off of the pads. Geckoadhesion has also shown ability to manipulate micro-objects. Mengüç et al.[360] studied the adhesion abilities of a single geckoinspired pillar of 35 µm; they demonstrated the pick-and-place of silicon microplatelets with dimensions 100 µm × 100 µm.

Soft grippers with geckoadhesion showed good versatility, adhesion to a broad range of objects, most of which are rigid and have relatively smooth surfaces. Potential challenges are represented by the handling of objects with rough surfaces and the manipulation of soft, deformable objects. For the former, a potential solution can be the optimization of the shape and materials of the microfibers. Enhancing the bending behavior of geckoadhesion pillars has led to improved adhesion performance on rough surfaces.[361] Microspines are also a good candidate that showed excellent grasping ability on rough surfaces such as of concrete and rocks.[362] The latter could be addressed by fabricating the grippers with highly compliant materials; however, such strategy can lead to issues when releasing the object.

5.3. Other Adhesion Technologies

Vacuum can generate adhesion through the negative pressure induced at the interface between the gripper and the object.[363] Suction cups made of compliant materials exploit this mechanism, and are widely used in industry. **Figure 14**a,b shows examples of compliant suction cups commercially available.[364,365] In suction grippers, vacuum can be achieved either actively or passively.[366] Suction works only on smooth, nonporous surfaces because one needs to establish a good seal between the suction cup and the object. Figure 14c shows an octopus-inspired tentacle composed of a pneumatic bending actuator equipped with suction cups whose vacuum adhesion can be controlled actively through an external compressor.[367] The device combines grasping by suction to the folding of the tentacle around the object; it achieved the holding of a rolled magazine, a metallic pipe, a ball, and a plastic water bottle. Researchers explored the use of a bidirectional EHD pump to realize a miniaturized suction cup.[368] By switching between positive and negative pressure of the EHD pump, they showed the holding and release of a small paper sheet weighting 2.9 g.

Capillary adhesion has been used specifically for manipulation of micro-objects.[369–372] Grippers using this adhesion technology exploit capillary lifting force of a liquid (generally water) bridging the gripper and the object. Picking and releasing of the object can be controlled by applying a low voltage electric field to the liquid bridge, changing the contact angle (i.e., changing the surface tension). Grippers in this category are suitable for micromanipulation, since the capillary force is dominant at the micro-nanoscale. Figure 14d shows the operation of a capillary gripper picking up a micro-object made of polystyrene.[372] The object, which has diameter of 30 µm, is lifted using the thin water layer formed on the gripper due to ambient humidity.

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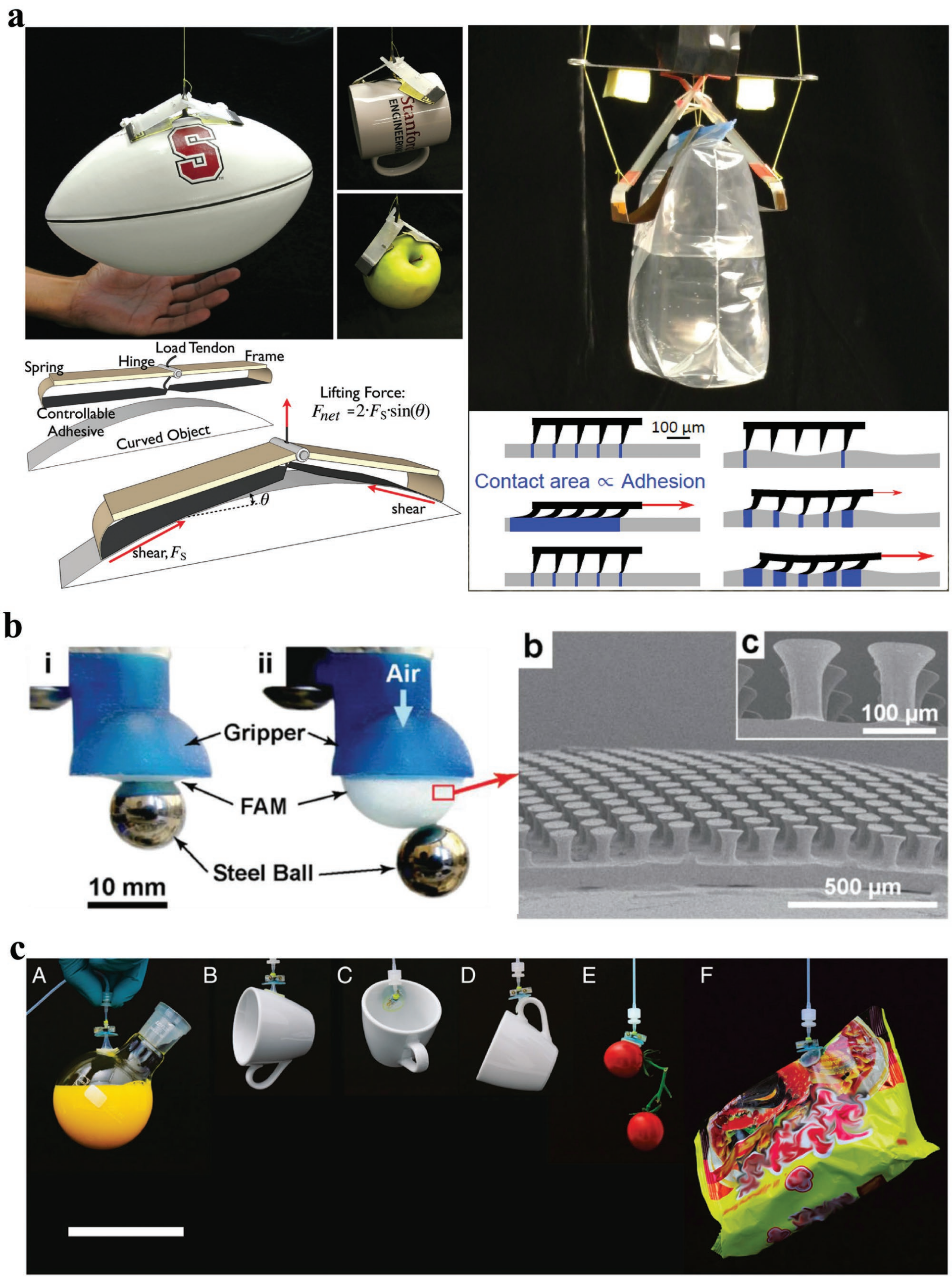

Figure 13. Soft grippers using gecko-adhesion. a) Combination with a passive mechanism that pre-loads microfibers arranged on a flexible film substrate. Left) Reproduced with permission.[355] Copyright 2015, IEEE. Right) Reproduced with permission.[356] Copyright 2015, ASME. b) Combination with fluidic elastomer actuators (FEAs) (an inflatable membrane).[95] c) Holding of different items by an elastomer membrane with mushroom-shaped microfibers. Reproduced with permission.[358] Copyright 2017, The Authors, published by National Academy of Sciences.

Since the capillary grippers interface objects via liquid, they are advantageous for minimizing the risk of potential damages. However, their grasping performance on materials with different surface energy remains unclear. There are other adhesion technologies paving the way for soft grippers. Examples are electrically actuated suction cups,[373] and octopus-inspired nanosucker arrays film.[374,375] Once integrated, they could bring novel functionalities and applications to soft grippers.

6. Sensing Technologies

Embedding stretchable sensors in or on soft grippers would greatly enhance the ways in which the grippers can interact with the objet being manipulated. Compared to more conventional "hard" grippers, compliant grippers offer a much larger contact area with the target, allowing for a broad range of sensing methods that can be spatially resolved over the object. One could embed sensors in the gripper so that, while the

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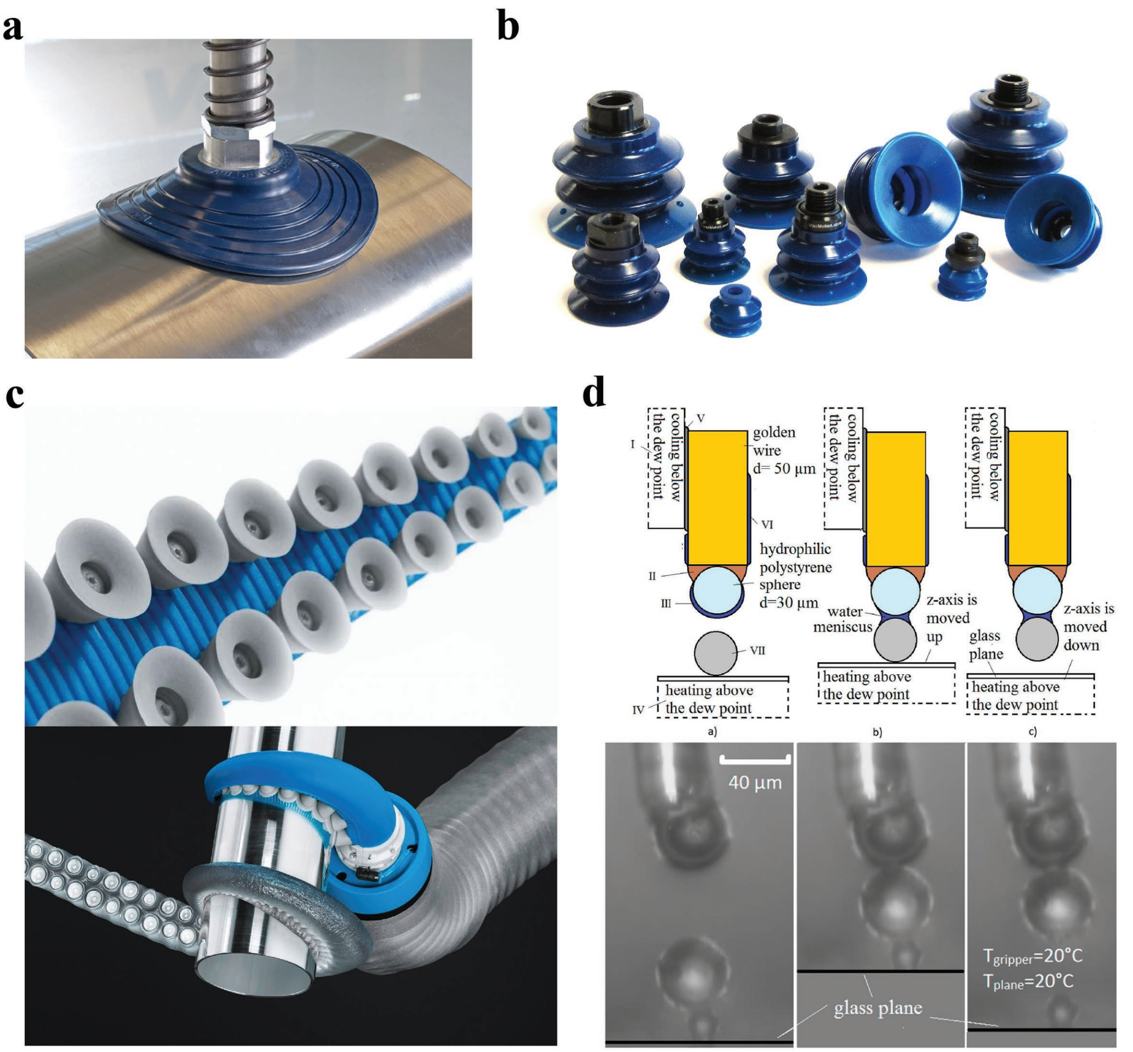

Figure 14. Soft grippers using other adhesion technologies. a) A commercially available compliant suction cup. Reproduced with permission.[364] Copyright FIPA GmbH. b) Products of compliant suction cup in different size. Reproduced with permission.[365] Copyright VacMotion Inc. c) Suction cups integrated in an octopus inspired tentacle made of a fluidic elastomer actuator (FEA).[367] Reproduced with permission. Copyright Festo AG & Co. KG. b) Operation of a capillary gripper picking up a micro-object. Reproduced under the terms of the CC BY license.[372] Copyright 2017, The Authors, published by MDPI.

object is being manipulated (or even before touching), one simultaneously obtains information on shape, elasticity, temperature, surface texture, mass, color, presence of biochemical markers, etc. One can envisage an intelligent soft gripper thus able to respond to the presence of an object, or to specific attributes of an object (e.g., making a simple decision such as closing when near an object, or making more complex decisions such as determining whether a banana is ripe based on mechanical properties and skin color).

Key challenges for sensors designed for soft gripper are that the sensors must: i) be at least flexible, but preferably stretchable, ii) they must not add significant stiffness and thus restrict motion of the soft gripper, while allowing for distributed sensing with high spatial resolution. Biocompatibility, robustness, reliability, simple readout, stability, and ease of integration are desired. Several recent review articles have been published on e-skins,[376–380] on stretchable and wearable strain sensors,[381] and on sensors used in soft robotics.[9] We summarize here some key sensing technologies that could be integrated with soft grippers.

Stretchable strain sensors, and related force and pressure sensors, are most commonly based on resistive or capacitive structures. In both cases, electrodes that conduct at high strain are needed. The most widely used electrodes are silicones loaded with conductive particles such as carbon black, carbon nanotubes, or metal nanowires, though many other stretchable electrode types have been reported, as reviewed in ref. [382]. The speed of these sensors is generally of order 100 ms, limited by the mechanical response of the elastomer.

Capacitive sensors respond to geometrical changes: the area of the electrodes and spacing between electrodes change when the sensor is stretched. Resistive sensors rely on geometrical changes but also on change in conduction mechanisms between nanoparticles, or on cracking at large strain.[381] While

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easier to implement, resistive strain sensors show a history-dependent resistance, making calibration quite challenging. Capacitive sensors are nearly insensitive to the conductivity of the electrodes, and are preferred for larger strains, but require a more complex readout scheme.[383] Capacitive sensors have been integrated for example in electroluminescent skin,[384] and can be made to be very robust.[385]

Based on FEAs, several soft grippers with embedded resistive strain sensing have been developed.[96,97,100–105,123] They mostly use strain sensors to detect curvature of gripper's finger, or to obtain contact information. **Figure 15**a displays a resistive sensor embedded soft gripper developed by Koivikko et al.[97] The curvature sensor is integrated in a multi-chambered FEA as a part of the strain limiting substrate, and is made by screen-printing of either silver ink or carbon ink. There are also FEA grippers combining flexible, resistive strain gauges that are commercially available, as shown in Figure 15c,d, showing one finger of the sensorized grippers developed by Elgeneidy et al.[102] and Wang and Hirai,[103] respectively. Capacitive sensors have also been employed in the form of a sensorized skin in tendon-driven soft grippers (Figure 4g, see also Section 3.1.2).[59] Gafford et al. developed a tendon-driven surgical gripper (Figure 15b) with embedded microelectromechanical systems (MEMS) pressure sensor on its fingertips.[51] Ho implemented a fabric capacitive sensor as a strip of compliant gripper that wraps object,[25] and also created elastomer fingers that can act as a compliant capacitor, leading to acquisition of proximity and contact information.[386]

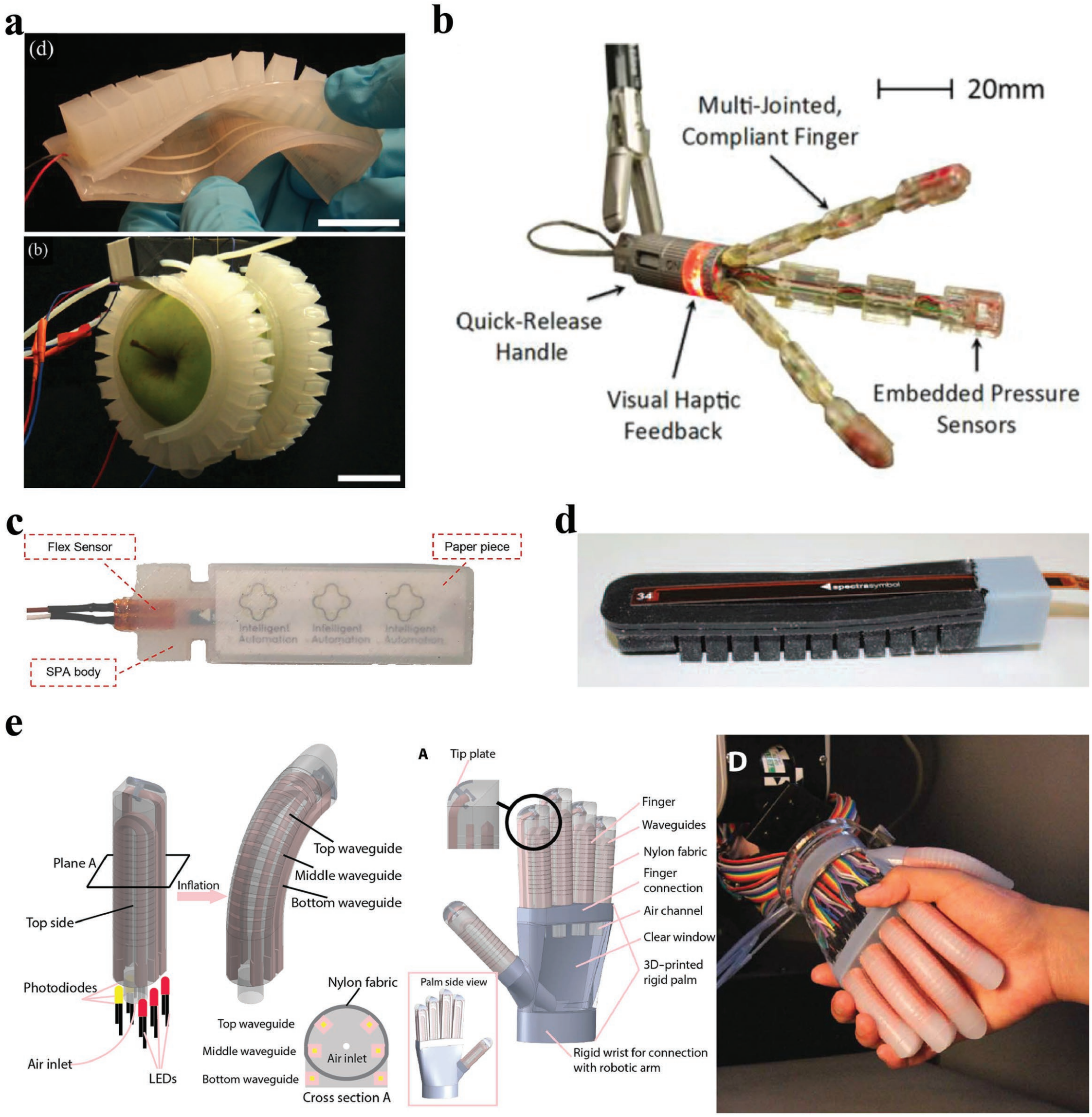

Figure 15. Soft grippers with integrated sensors. a) A resistive curvature sensor embedded in a fluidic elastomer actuator (FEA). Reproduced with permission.[97] Copyright 2018, IEEE. b) Tendon-driven fingers with integrated MEMS pressure sensors. Reproduced with permission.[51] Copyright 2014, ASME. c,d) A finger of FEA grippers equipped with embedded commercially available resistive strain gauges. c) Reproduced under the terms of the CC BY license.[102] Copyright 2017, The Authors, published by Elsevier. d) Reproduced with permission.[103] Copyright 2016, IEEE. e) FEA fingers with stretchable optical waveguides. Reproduced with permission.[98] Copyright 2016, AAAS.

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Optical methods based on lossy waveguides have been developed, and were integrated into an FEA soft gripper by Zhao et al. (Figure 15e).[98] Using soft polymer optical fibers is an appealing method, as it can allow detecting chemical compounds, in addition to pressure sensing.[387–389] A conventional optical flexure sensor has been implemented in a tendon-driven compliant gripper.[46] Embedding small magnets in an elastomer a few mm above a two or three axis Hall sensor or matrix of Hall sensors allows the measurement of normal and shear force,[390–394] allowing both tactile sensing as well as use in closed-loop control. The method is fast, and has low hysteresis. By choosing the elastomer material and thickness, it can be tuned to respond a wide range of forces. Using a matrix of Hall sensors allows making the device insensitive to fixed external magnetic fields. This method requires integrating Hall sensors and adds some bulk due to the magnets and surrounding elastomer.

By combining rigid elements with soft elastomers, a broad range of sensors can be integrated in deformable arrays.[395–397] For instance, ECG sensors, pH sensors, and temperature sensors have been reported in a compliant device that could be mounted on a rabbit heart.[398] Using a 1.4 µm thick substrate, Drack et al.[399] developed extremely compliant temperature sensors and electronics. Sensors will play an essential role in enabling grippers to respond to the environment and will greatly increase the application areas for soft grippers.

7. Summary and Outlook

There has been tremendous progress in the performance and versatility of soft grippers since the first tendon-driven concept in the late 1970s. This progress has been made possible both by new concepts and by the improved understanding and development of compliant and active materials. In this review, picking up objects was often shown as the main illustration of soft grippers. However, as the field of soft robotics blossoms, soft gripper technologies will be used not only as end effectors, but as the means to actuate the entire body, leading to locomotion, body shape control, prehension, and thus enable key functions of autonomous soft robots.

Advanced materials are at the heart of future soft grippers: force, speed, adhesion, kinematics, are all determined by the materials. Being soft and stretchable is central to most soft grippers concepts, and elastomers have been a material of choice thanks to wide range of commercially available formulations, high strain at rupture, and low stiffness. However, the use of elastomers has often meant a lack of long-term robustness, though effective solutions have been demonstrated for devices that have been commercialized.[143,144,262] Progress in self-healing materials will be important for reliable grippers. Phase change materials are poised for a larger role. For instance, new SMP with sharper transitions, or SMPs combined with conductive particles to enable flexible integrated Joule heating are active research areas. Taking the device life-cycle into consideration leads to a larger role for recyclable, biocompatible, degradable, or even edible compliant materials. This paves the way for new application scenarios where soft robots vanish after use, but requires the development of new materials and new processing methods.

One important trend in compliant grippers is the combination of different technologies and different materials sets. This review includes several examples of such combinations, such as a two-fingered gripper with both DEA bending and electroadhesion (Figure 12d),[175] or the FEA combined with LMPA (Figure 10d,e).[91] Combining materials and operating principles often adds complexity to the fabrication process or the control, but can greatly enhance performance.

Soft robotics have been demonstrated across a wide range of size scale, from a hundreds of µm[245] to over one meter.[133] The scaling laws are well understood for all actuation principles presented in this review. When object dimensions are reduced below ≈50 µm, surface forces) become comparable to inertial forces, and different grasping strategies are called for.

Most of gripping principles reported here were demonstrated in air, and could also be used underwater, or even in vacuum. Pneumatic systems are particularly easy to adapt to different external pressures. Electroadhesion and dry adhesion work well in vacuum, but are not effective in liquid environments. Actuators relying on heating and cooling can have very different time constants if placed in liquids or in air.

Embedding distributed sensing in soft grippers will enable more autonomous or intelligent use of soft grippers, by providing a means for the gripper fingers to not only sense contact or proximity to an object, but to acquire a broad range of information about the object, and then act on that information. Flexible strain and pressure sensors have been incorporated as illustrated in Figure 15. The sensors must either be stretchable and soft, or if they are rigid (e.g., MEMS silicon-based inertial measurement units (IMUs) or thermal sensors) they must then be so small compared to the scale of the gripper that they can be integrated without changing the overall compliance, or at least without changing the compliance of key contact points. If a gripper could, by grasping an object, obtain information on overall shape, elasticity, temperature distribution, surface texture, mass, color, or the presence of biochemical markers, vast new fields of applications become possible.

Ongoing research to address key challenges in soft and active materials, processing methods, gripper architectures, distributed sensors, control methods, and local information processing pave the way for a wide range of applications for soft robotics grippers, in manufacturing, haptics, for drug delivery or even object manipulation in space.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

adhesion, smart materials, soft grippers, soft robotics, variable stiffness

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