3D Printing of Robotic Soft Gripper: Towards Smart Actuation and Sensing

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Abstract

Unlike traditional hard grippers, soft robotic grippers are commonly made of soft materials so that the soft grippers can produce motion via elastic deformations of their compliant components. The advantages of compliance allow soft grippers to effectively eliminate shocks caused by hard contact, which usually occurs when a hard robotic gripper manipulates a hard object. Until now, the soft robotic grippers are able to operate numerous objects with irregular geometries and different textures. Besides, with the help of embedded sensors, soft robotic grippers have facilitated the growing automation of many tasks, which were thought to be far too delicate for robotic manipulation. This paper will review the advancement in soft robotic grippers. The paper will first introduce the actuation technologies and followed by the design and fabrication techniques. The use of 3D printing techniques in the fabrication of the soft gripper will also be discussed. It will then highlight the challenges and future outlook in the fabrication of soft grippers and sensors.

1. Introduction

The advent of robotic systems to complement or replace humans to execute repetitive or risky tasks has been widely explored in recent years [1]. Handling of geometrically complexed objects continues to be a difficult task, and robotic grippers would need to interact with the surroundings and manipulate items with a high moving speed in order to carry out specific tasks in various applications such as automated manufacturing processes [2], minimally invasive surgery [3], and space exploration [4]. The use of grippers also sees high demand in agriculture and food industries' applications such as hygienic food handling [5, 6] and fruit harvesting [7].

Conventionally, parts are handled by suction-based and magnet-based solutions. However, there are limitations to those techniques. For example, the suction-based techniques are susceptible to oil and dust, limited to simple geometry whereas the magnet-based techniques cannot handle non-ferrous parts, and would magnetize ferrous parts, causing magnetic dust to accumulate and cause scratches. Claw grippers are rigid, bulky, and inefficient. Due to its rigid nature, it is less compliant/adaptive to the parts. They also do not accommodate extensive customization of design features. This means that a new claw design would be required for a new product with different shapes. It requires time, effort, and money to have a new claw design. Due to this, only a small fraction of the items can be handled by robotic grippers.

Soft grippers are being developed to tackle the shortcomings of conventional robotic grippers in interacting with humans and in handling hard-to-handle fragile and biological objects. One advantage of the soft grippers is that the flexible gripping surfaces guarantee that there is maximum compliance to the object being grasped, thus improving the grasping of any oddly-shaped objects. In terms of safety, the soft nature of the grippers reduces the chance of causing serious injury to the human operators in the event of a collision as impact forces are spread over a larger area [8]. However, the creation of the soft grippers normally involves multifaceted fabrication processes which comprise several molding processes, assembling, and wax melting. The industrial robotic arm can achieve very high acceleration during pick and place tasks. Typical speed and acceleration requirements for an arm robot are 2 m/s and 10 m/s^2, respectively, whereas in very high-speed applications, speed and acceleration can reach 10 m/s and 100 m/s^2, respectively [9]. The underlying soft material poses challenges in resisting disturbances or maintaining their shape under intense inertia, which can limit their applicability.

To address the problem, several studies have been attempted to develop soft grippers with the ability to vary stiffness by adding a stiffness-changing unit into the system [10-12]. Several limitations were identified in the fabrication of stiffness-tunable grippers: the complexity of mold design, individual differences in performance caused by manual operation, and a time-consuming fabrication process. As the stiffness-varying feature often entails an extra manufacturing process and incorporation method, the fingers/grippers are quite large, and this can restrict their use in handling tiny parts [9].

3D printing offers a way to produce low-cost smart soft grippers as 3D printing enables iterative design with a short lead time. This is because grippers can be manufactured without the need for molds and tools [13]. The layer-by-layer manufacturing technique also allows multi-material parts to be fabricated enabling us to create grippers with higher design complexity without a significant increase in cost[11]. Additionally, various 3D printing techniques with the ability to deposit conductive inks have been developed[14]. Coupled with robotic arms, circuits, and sensors can be printed directly on the surface of the geometrically complex structures through conformal printing[15], enabling the creation of multifunctional structures with sensing capability.

To date, various soft gripper designs using different actuation and control methods have been demonstrated. The advancement in 3D printing has changed the way grippers are being developed. Taking advantage of the manufacturing flexibility of 3D printing, a new generation of soft grippers with more innovative designs can become a more integral part of the human environment. This paper reviews the current state-of-the-art gripper designs, fabrication methods, actuation, and sensing techniques.

2. Actuation technologies

Soft robotic grippers are commonly made of soft or compliant materials. Theoretically, they have infinite degrees of freedom (DOF) and their deformations can be actuated in many different methods. From the perspective of material properties, physical principles, and architectures of soft grippers, this section will mainly discuss four representative actuation technologies: (a) contact-driven actuation (b) tendon-driven actuation (c) fluidic actuation, and (d) shape memory alloy actuation. The advantages and applications of 3D printing in the creation of features or parts that are useful for different actuations will also be discussed.

2.1. Contact-driven actuation

Contact-driven actuation is a passive actuation method that produces elastic deformations by passively adapting to the shape of the object when the grippers come into contact with the object. The key feature of such actuation is that active elements do not exist inside the soft grippers. The passive deformation of the compliant element depends on the external mechanical inputs. Hence, contact-driven grippers are commonly actuated by external motors that can provide translation and rotation of the grasping components. Due to this feature, this type of soft grippers is able to achieve high mechanical robustness. A typical example of contact-driven actuations is the Fin Ray structure shown in Figure 1A, which is inspired by fish fins [16]. The fin-like structure deforms to conform to the surface of the object when it comes into the object. Once the bending of the fin structure is adequate to grasp the object, the gripper can pick up and hold the object. Similar compliant structures have been developed for a wide range of tasks pertaining to harvesting vegetables in a greenhouse, grasping eggs and fruits, as well as handling office supplies.

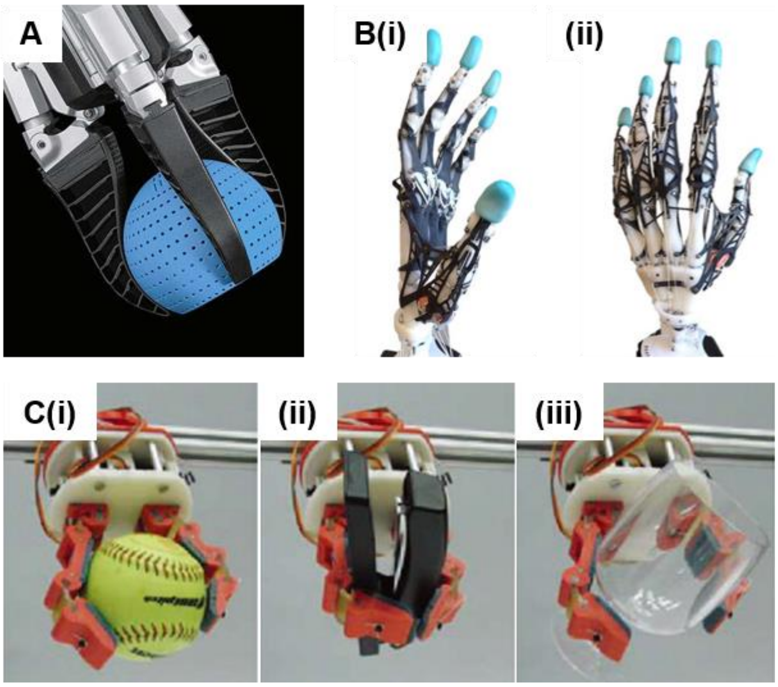


Figure 1 Soft robotic grippers using contact-driven and tendon-driven actuations. (A) Fin Ray robotic gripper. Reproduced under the terms of the CC-BY Creative Commons Attribution 4.0 International License. [16] Copyright 2016, Frontiers Media S.A.. (B) Anthropomorphic tendon-driven. Reproduced with permission, [17] Copyright 2016, IEEE . (C) Tendon-driven with elastic hinges. Reproduced with permission, [18] Copyright 2016, IEEE.

Contact-driven actuation relies greatly on the elastic deformations of the materials to adapt to the shape of the object. A wide range of materials have been developed and known to be printable. For instance, TPU with a shore hardness of 85A has been widely used in FDM to create soft structures. The ability of FDM to print different infill patterns and densities allows more design flexibility to tune the softness of the printed parts [19].

2.2. Tendon-driven actuation

Tendon-driven actuation is also a passive actuation method that drives soft gripper to deform by pulling tendons or cables. This actuation method is inspired by human fingers and the corresponding devices generally consist of a multi-DOFs articulated component driven by tendons or cables. Tendons or cables can provide muscles-like functions. As these actuation methods allow the actuator to remotely drive the compliant components, soft devices based on this method are easier to miniaturize and to be lightweight. A representative example of tendon-driven actuation is an anthropomorphic hand demonstrated in Figure 1B [17]. This tendon-driven hand faithfully mimics the placement of muscles and the shape of bones. Another example of tendon-driven actuation is shown in Figure 1C, in which a tendon-driven hand exhibits its capabilities of grasping a wide range of items, including a tennis ball, stapler, and glass cup [18]. Additionally, these fingers of the tendon-driven hand are fabricated using 3D printing techniques. Despite having the advantages mentioned early, tendon-driven actuations also have mechanical limitations such as fatigue, nonlinear friction, backlash hysteresis, and inadequately transmitted forces [20].

Tendon-driven grippers have internal channels for the cables. Conventionally, these internal channels would require careful design consideration such as the placement of the inserts when design a mould for the grippers. 3D printing greatly simplify the fabrication process of the tendon-driven grippers. The ability of 3D printing process to pause during the print to insert functional components such as the cable allows the creation of fully functional grippers straight out of the 3D printer.

2.3. Shape memory alloy actuation

Shape memory alloys are a type of smart material that exhibits the shape memory effect. Specifically, such material is able to return from a temporarily deformed shape to its original shape. The actuation mechanism of shape memory alloys is generally controlled by the heating process. The thermo-mechanical behavior of such material depends on phase transformation, i.e., austenite phase and martensite phase, which is known as “martensitic thermoplastic transformation”. The Austenite phase exhibits higher stiffness like many metals whereas the martensite phase has low stiffness more like an elastomer. A typical shape memory alloy used as actuators is Nickel-titanium [21]. As a kind of actuators, the shape memory alloys have some excellent properties, such as high actuation energy density, high localized forces, nonmagnetic behavior, and high corrosion resistance. In addition, this type of smart material is more easily fabricated into different shapes. Despite these advantages, the use of shape memory alloys needs to handle the adaptability to the object. One feasible way to construct soft grippers based on the shape memory alloy is the combination of shape memory alloys with flexible elements, such as springs, beams, and hinges [22-24]. A representative example of such actuation is the MINIR-II robot developed by Kim et al., as shown in Figure 2A [25]. This robot is actuated by the spring actuator, which is made of shape memory alloys. Another method is the integration of shape memory alloys and soft materials [26-29]. Using this method, a robotic hand was developed by She et al, as shown in Figure 2B [30]. This device exhibits adaptability in grasping a wide range of items, from a wire spool to a thin card. Since the actuation speed of shape memory alloys relies on the cooling time constant, future research on soft grippers based on shape memory alloys could focus on actuation speed and hysteresis.

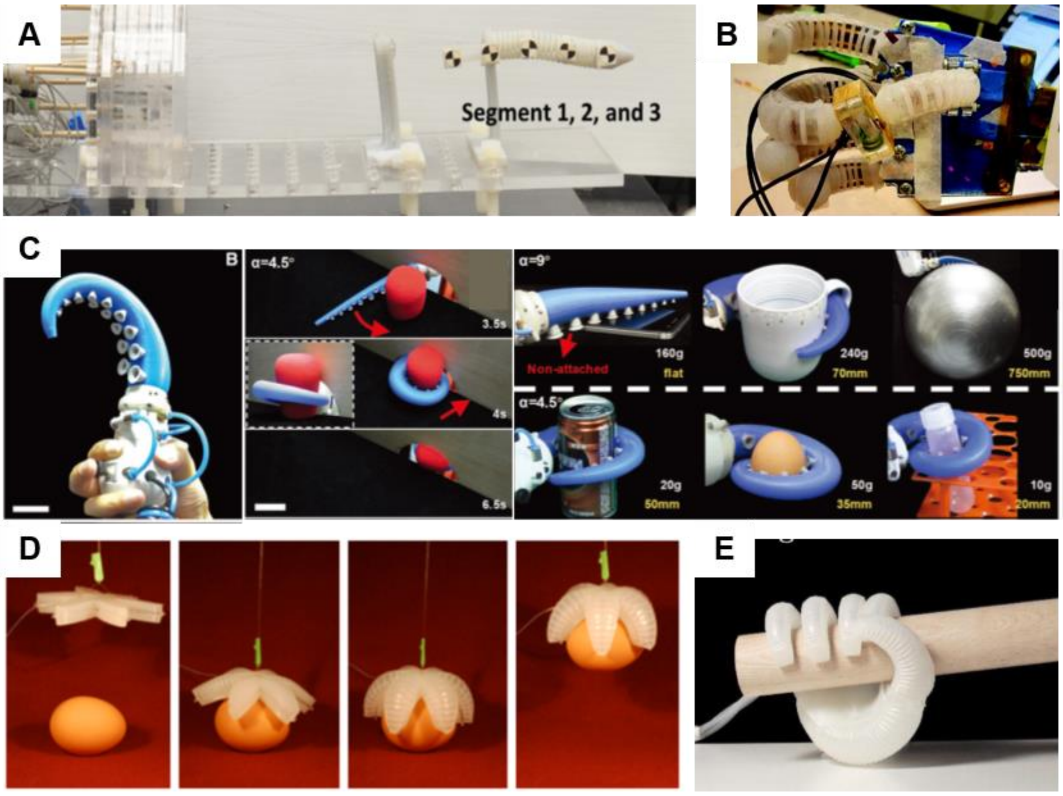


Figure 2 Soft robotic grippers using shape memory alloys and fluidic actuation. (A) MINIR-II. Reproduced with permission, [25] Copyright 2015, SPIE. (B) Elastomeric fingers using shape memory alloy. Reproduced with permission, [30] Copyright © 2016, Mary Ann Liebert, Inc. (C) Octopus arm-inspired tapered soft actuators. Reproduced with permission, [31] Copyright © 2020, Mary Ann Liebert, Inc. (D) Soft grippers embedded pneumatic networks Reproduced with permission, [32] Copyright ©2011 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim. (E) Bio-inspired robotic hand. Reproduced with permission, [33] Copyright © 2016 SAGE Publications.

The fabrication of NiTi shape memory alloy using 3D printing techniques has been attempted. 3D printing has enabled in-situ alloying which enables the creation of functionally graded materials by tuning the material compositions, process parameters or meso-structures. Clare et al fabricated NiTi samples using SLM that showed a gradual phase transformation by optimizing the laser power[34]. Lu et al. fabricated Ti-rich $Ti_{50.6}Ni_{49.4}$ SMA with a high ultimate tensile strength of 776 MPa and a high recovery rate of 98.7%. The group found that nearly full dense SMA with good crack resistance can be achieved by controlling the energy input of the laser source. More information on the fabrication of the 3D printed SMA can be found in [35].

2.4. Fluidic actuation

Fluidic actuation is a typical actuation for soft robotics in the past three decades. Such actuation is achieved by fluid (pressurized hydraulic or compressed air) on a chamber made of elastomeric materials. Hydraulic actuation has the advantages of high output power and fast response. However, its application in soft robotic grippers is limited due to the large mass and viscoelastic coefficient. Fluidic actuation under compressed air is also called pneumatic actuation. Pneumatic actuation has been widely used for soft robotics due to its advantages, such as light weight, easy fabrication, low cost, and no pollution [36, 37]. Pneumatic-based actuators are generally designed to be asymmetrical profile so that the inflation of the chamber can produce a bending motion to grasp the object. A representative example of pneumatic actuation is the octopus-inspired soft robotic gripper shown in Figure 2C, which is designed to mimic the bending motion of an octopus tentacle [31]. Due to its flexibility, adaptability, and agility, the octopus-inspired soft gripper can effectively grasp a wide range of objects with different shapes and sizes. Using the so-called PneuNets actuation method, Ilievski et al. developed a soft gripper shown in Figure 2D [32]. This soft gripper has six fingers and each finger can bend up and down. Together with six fingers, this gripper is able to pick up and hold an egg. Another example is the bio-inspired hand developed by Deimel et al., as shown in Figure 2E [33]. Fiber-reinforced fluidic actuators are used to drive the bioinspired soft hand to mimic various human grasps. Further work on fluidic actuation could handle the improvement of external pumps and compressors as these kinds of components are often heavy that affect the application of fluidic actuation.

In fluidic actuation, air-tightness and water tightness are critical in ensuring proper actuation of the gripper. Air-tightness is strongly related to the porosity of the printed parts. It was found that 3D printing technique like stereo lithography can produce pore-free parts, whereas fused deposition modelling-printed parts exhibit higher porosity [38]. The study has shown that the leak rate of the FDM printed parts was 1.51 x 10^{-5} Pa m^3 s^{-1} whereas the leak rate of the SLA printed parts was 4.95x10^{-8} Pa m^3 s^{-1}, which is around 3300 times lower[38]. With proper optimization of the print parameters, 3D printed parts with good air-tightness and water tightness are achievable. For instance, 3D printed air connectors and pneumatic finger grippers that are able to withstand 4 bars without leakage have been fabricated by optimizing the nozzle size, line width and wall thickness of the air chamber [39].

2.5 Tunable stiffness technologies

Tunable stiffness techniques have been used in the field of soft robotics. Tunable stiffness-based soft grippers are generally developed based on tunable stiffness materials and structures. Such soft grippers are commonly designed to have two stiffness configurations: the ‘soft’ configuration and the ‘hard’ configuration. Soft robotic grippers can deform freely in soft configuration, while their stiffnesses switch to be stiff when they come into their hard configuration. The tunable stiffness method allows the soft grippers to achieve high holding force so that tunable stiffness-based soft grippers are able to fulfill a wide range of tasks requiring relatively high load capacity, such as grasping, supporting tools, and the manipulation of objects. Furthermore, the grasping strategy based on tunable stiffness method is efficient for a wide range of objects with irregular geometries. A representative of tunable stiffness-based grippers is the “Universal Robotic Gripper” developed by Brown et al., as shown in Figure 3A [40]. This device has a chamber made of highly deformable materials. There are some small particles inside the chamber. By tuning its stiffness, this gripper is able to grasp objects with irregular geometries. Specifically, the gripper approaches and envelops the object in a soft configuration. When the object is enveloped by the soft gripper, the stiffness of this gripper becomes stiff by evacuating air from the chamber. This enables the object to be manipulated. Another example of a tunable stiffness-based gripper is the robotic hand with two soft fingers shown in Figure 3B [41]. Each finger is equipped with an enclosed chamber filled with small granular material. It is shown that this soft robotic hand is able to handle chopsticks to manipulate some small objects. Combining particle jamming method and fluidic actuation, Li and his colleagues proposed a passive particle jamming principle that does not require any vacuum power, as shown in Figure 3C [42]. Despite having the advantages mentioned before, tunable stiffness-based grippers, especially for particle jamming, are unable to manipulate flat and soft objects. Further work on particle jamming-based grippers could focus on improving their capabilities of handling flat and soft objects, such as plastic foils.

3D printing enables the creation of structured fabrics, which are almost impossible to be fabricated using any conventional manufacturing techniques. These structured fabrics are soft and conforming to the surface when they are loosely packed and get stiffened when enveloped with confining pressure. Wang et al. showed that the fabric, with interlocking particles that have good tensile strength, can be 25 times stiffer compared to the relaxed configuration[43].

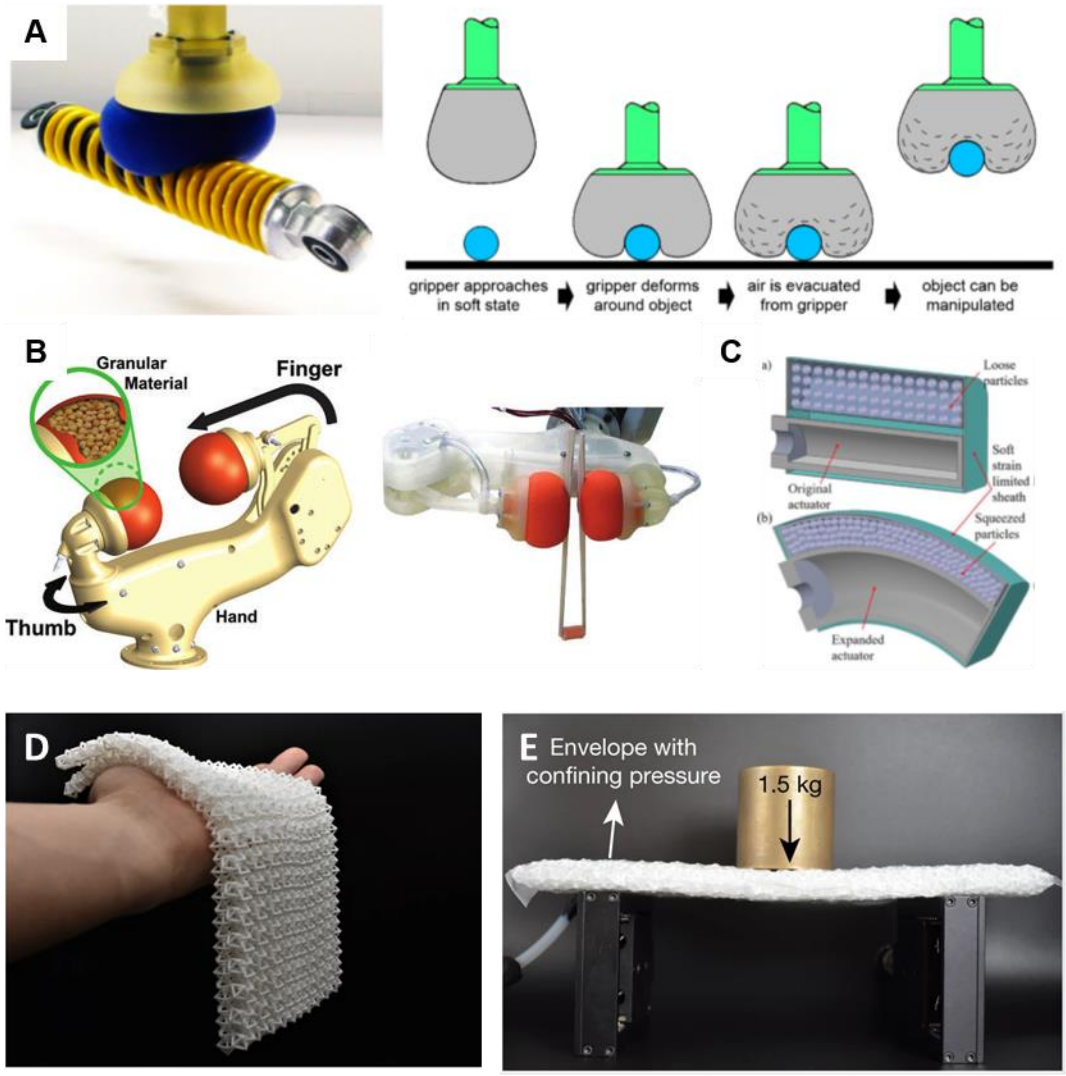


Figure 3 Tunable stiffness-based soft robotic grippers. (A) The universal soft gripper using granular jamming, and its working principle. Reproduced with permission, [40]. (B) Soft JamHand. Reproduced with permission, [41] Copyright © 2017, Mary Ann Liebert, Inc. (C) Soft grippers using passive particle jamming. Reproduced with permission, [42] Copyright © 2017, IEEE. (D) lattice fabric in soft state (E) lattice fabric in that stiffens in vacuum. Reproduced with permission, [43] Copyright © 2021, The Author(s), under exclusive licence to Springer Nature Limited.

2.6 Controllable adhesion technologies

Adhesion is an interface attraction between two contact surfaces. Due to the existence of normal traction, the contact interface also leads to a large shear friction force, which is beneficial for soft grippers to pick up and hold objects. There are two typical adhesion technologies, i.e., electrostatic adhesion and gecko-inspired adhesion. Electrostatic adhesion is a type of electrostatic attraction that occurs between oppositely charged particles. Since the interface needs to be charged, a high external electrical field is generally required in this method. It is shown that electrostatic adhesion is effective for objects with both smooth and rough surfaces. Soft robotic grippers based on electrostatic adhesion have been reported. For instance, Grabit Inc. developed an electrostatic adhesive soft gripper with eight fingers shown in Figure 4A [44]. Each finger is made of flexible PCBs with interdigitated electrode patterns. Using electrostatic adhesion, this gripper can grasp a series of items, such as a cookie box, and metallic cans. Figure 4B shows another electrostatic adhesive gripper developed by Schaler and his colleagues [45]. This gripper is able to handle a flexible PET film using its eight fingers made of flexible-PCB. Combining electrostatic actuation and electrostatic adhesion, Shintake et al. investigated a novel soft gripper shown in Figure 4C [46]. The proposed gripper has the capability of handling an egg, a deformable water balloon, and flat paper.

3D printing of flexible sensors and circuits has become more popular. Inkjet printing and aerosol jet printing are the 2 common techniques for printing electrical circuits and sensors. Interdigitated electrode patterns have been 3D printed owing to its ability to process a wide range of materials including inorganic, carbon materials, polymers and UV curable resins [47, 48]. The ability of the aerosol jet system to perform conformal printing enables the direct fabrication of conductive circuits onto the complex structures [49].

Gecko-inspired adhesion is a synthetic directional adhesive induced by van der Waals interaction between two contact objects. Soft robotic grippers based on gecko-adhesion are generally designed to have a lot of microstructures on their surface. When the grippers come into contact with objects, van der Waals interaction can be activated by pressing the microstructures against the object surface so that the gripper can pick up and hold the objects. Applying a peeling force to the microstructures can deactivate van der Waals interaction. Applications of gecko-inspired adhesion include wall climbing robots [50, 51], surface climbing devices [52], and object manipulation in space [53]. A representative of soft grippers based on gecko-inspired adhesion is an inflatable membrane gripper developed by Song and Sitti, as shown in Figure 4D [54]. The surface of this soft gripper is covered with numerous micro-fibrillar structures. The contact interface between the gripper and object is controlled by the inflation of the membrane so that this soft gripper can grasp the steel ball by large contact area and release the ball by peeling the membrane from the object by injecting air into the chamber. Similar research on adhesive soft grippers is shown in Figure 4E [55]. This device controls the adhesion by tuning the internal pressure of its membrane. It is shown that this gripper can handle various 3D objects, such as a rounded glass flask, a coffee cup, a pair of cherry tomatoes, and a plastic bag. Gecko-inspired adhesion is efficient for soft and flat objects, such as plastic foils, but is unable to handle objects made of low surface-energy materials, such as oily objects. Further work could look into the use of oleophobic materials and the combination of adhesion and other actuation methods.

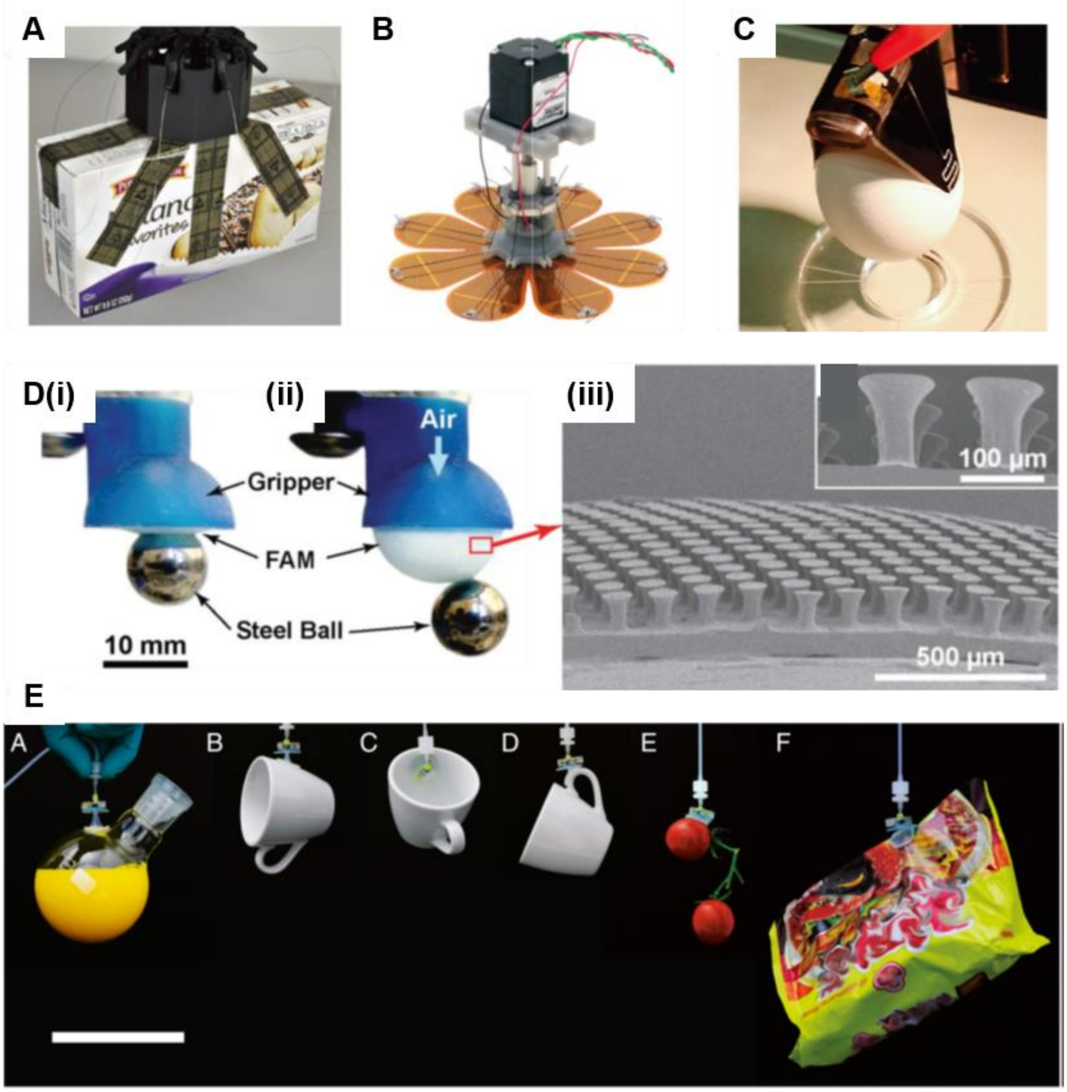


Figure 4 Soft robotic grippers based on controllable adhesion. (A) Electrostatic adhesive soft gripper [44]. (B) Soft gripper with Flexible-PCB. Reproduced with permission, [45] Copyright © 2017, IEEE. (C) Soft gripper with dielectric elastomer. Reproduced with permission, [46] Copyright © 2015 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim. (D) The soft gripper using gecko-inspired adhesion [54]. (E) Adhesive soft gripper. Reproduced with permission, [55].

Gecko-inspired adhesion relies greatly on the microstructures on the surface. These microstructures are typically in the range of a few micrometres. High-resolution 3D printing has receive wide attention as it emerges as a promising solution for creating multifunctional 3D parts with high-aspect-ratios. Two-photon polymerization (TPP), projection microstereolithography, direct ink writing, and electrohydrodynamic printing are some of the few 3D printing techniques that are known to achieve sub-micron print resolution [56]. Multimaterial printing has also been successfully demonstrated at the sub-micron level using the TPP technique [57, 58]. The advancement of the microscale 3D printing opens up the potential to have more tailor-made microstructures to improve the adhesion at the surface.

3. Design and Fabrication of grippers

Thus far, various gripper designs have been developed. Some designs are inspired by nature, while some are based on the understanding of material behaviors and various power transmissions mechanisms. In this section, various types of gripper designs would be discussed in detail in terms of performance, advantages, and disadvantages.

3.1. Nature-inspired

3.1.1 Human Fingers

Drawing inspiration from nature has been the most common and intuitive way to design soft grippers. Hands have always been an important part of the human body to perform functions such as grip, grasp, and pinch that enable us to perform daily activities such as handling and moving objects. The nimble human fingers enable us to perform precise movements such as writing and sewing. It is not surprising that the researchers took inspiration from it in the design of soft robotic grippers. In fact, most of the soft gripper designs were conceptualized based on the anatomy of the human hands. Regardless of the actuation mechanism, the main idea is to have a dexterous structure that can curl like human fingers. The shape-changing can be achieved by using tendons [59], pneumatic[60], hydraulic [61], or shape memory effect [27].

Ma and Dollar developed a simple, four-finger hand that consisted of 2 sets of cable-driven, underactuated fingers decoupled by an independent, central, axis of rotation [62]. The design enables finger-gaiting and yet preserves the passive adaptability of the underactuated finger pairs. Ahish and Xu have developed a robotic hand that closely imitated human hand anatomy in an attempt to study the underlying biomechanical and control characteristics of humans that enables robust, versatile, and dexterous motions [63]. Another study by Kantoudis and

Kiarokapis saw the creation of simple, anthropomorphic, underactuated robot hands comprising a tuneable differential mechanism [64]. The fingers of the hand can be controlled independently and have various grasping postures just by using a single motor and the differential mechanism. Robotic hand with underactuated fingers using a differential mechanism has also been attempted by Gosselin et al. [65]. The cable-driven anthropomorphic robotic hand controlled using a single actuator was enhanced for force transmission capabilities.

Shape memory alloys (SMA) wires have also been used in the development of finger grippers. The SMA wires were arranged such as they form a muscle pairing that can actuate in 2 forward and backward bending, allowing the finger to curl and extend like a real human finger. The advantage of the SMA wires is that they can be integrated into the mechanical structures without taking up a lot of space, and most importantly, without the need for bulky and complex gearing mechanisms, which could potentially lower the production cost [66]. The SMA wires change phase and return to their original trained shape once heated up. The gripping force is enhanced by wrapping the SMA wires a few times along the finger phalanxes, while the response time is shortened to ensure fast finger motion by using thinner SMA wires that can heat and cool rapidly.

Novel smart materials such as the ionic polymer-metal composite (IPMC) have been used in the fabrication of finger grippers. An IPMC typically has three layers, which contain metallic (platinum/gold/nickel) electrodes that are chemically plated onto a polymer substrate such as Nafion [67]. The IPMC was required to be placed in the correct position in the mold before PDMS resin is dispensed into the mold to take the shape of the gripper [68]. The three-finger gripper with 3 IPMC actuators per finger weighs around 6.63 grams and was able to achieve a maximum deflection of 2.76 mm by applying 5 V DC. The gripper is capable of handling objects smaller than 1 mm in dimension.

In pneumatic-actuated grippers, the curling of the finger is achieved by having several segments of air chambers that expand when being pressurized [69]. Soft materials such as silicone are used to fabricate the pneumatic-actuated grippers. Molding is conventionally used to form the shape of the soft grippers (Figure 5) [70]. The molding of the soft grippers is difficult, especially when dealing with internal channels and hollow chambers. For instance, in the cable-actuated grippers, silicone tubes were embedded into the soft grippers during the molding process to create the internal channels for the cables [59]. The silicone tubes would then be removed after the molding process.

In general, 3D printing techniques are used for direct fabrication of the soft finger gripper and the mould development for the finger gripper.

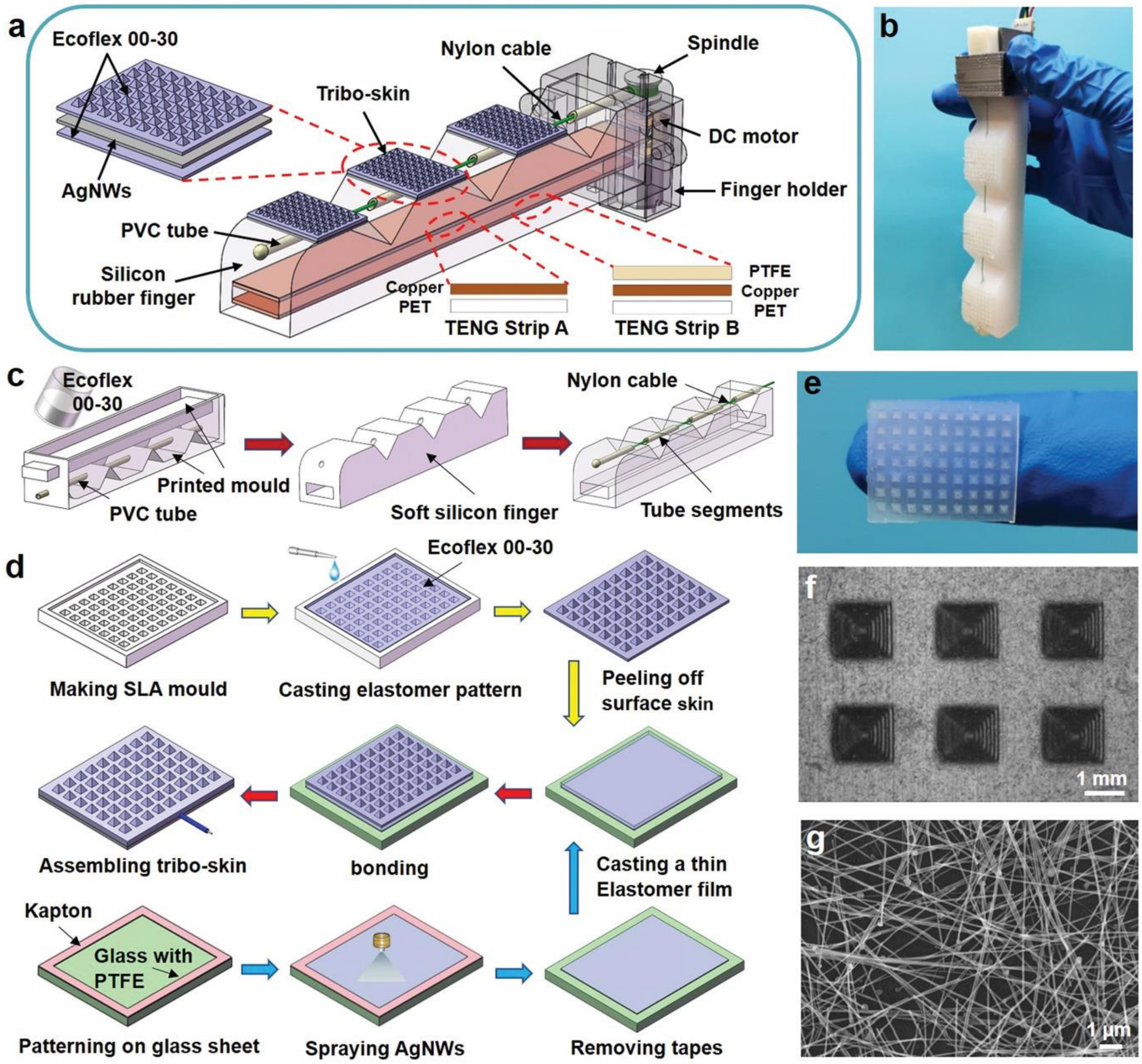


Figure 5 Development of smart, finger-like soft gripper. A) Diagram of the cable-driven soft gripper incorporated with tribo-skins and inner TENG strips for sensing. B) image of the manufactured gripper C) Manufacturing process flow for the soft gripper D) Manufacturing of the tribo-skin patch E) Image of the manufactured tribo-skin patch before the deposition of AgNW. F) SEM image of the array of the pyramid structures on the tribo-skin patch. G) SEM image of AGNW thin film electrode on the PTFE film. Reproduced with permission, [71] Copyright © 2020 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim.

3.1.2 Venus Flytrap

Many of today's inventions and innovations come from animals. They maximize their soft structure to adapt to the complex natural environment. [7] The Venus Flytrap, a plant that captures insects by trapping them in between its two leaves, is an excellent grasper in nature.

Thus far, a few soft gripper designs have been invented, taking inspiration from the Venus Flytrap. Shi and Guo utilized IPMC actuators to create a miniature robot, drawing inspiration from the Venus flytrap [72]. The robot is able to achieve a tip displacement of 10 mm and can carry a payload as high as 36 mN. Xu et al. fabricated a dielectric elastomer (DEA) actuated soft gripper that is able to open up its 2-leaf structure when voltage is applied [73]. DEAs are typically made up of at least 2 layers, which consist of a pre-stretched dielectric film and a slightly stiffer flexible frame. The restoring force of the pre-stretched film bends the frame into a minimum energy state. To straighten the frame and reduce the bending angle, voltages in the order of kilo-volts are applied across the dielectric elastomer. Constant high voltage will need to be applied to maintain the bending angle, which may degrade the dielectric film. Bi-stable dielectric elastomer actuated grippers have also been developed, which enables the gripper to switch to the grasping state by applying a short duration of voltage to the dielectric film. The dielectric actuated film is able to switch states quickly in the range of 0.1 -0.3 s when sufficient energy is provided.

The fabrication of the bi-state dielectric elastomer actuator is more similar to the conventional dielectric elastomer actuator, except that it has the pre-stretched dielectric elastomer on both sides of the flexible frame. Figure 6e shows the exploded view of the actuator structure. The elastomers (VHB4910 membranes (3M, USA)) were pre-stretched 4 times their initial length and bonded to the flexible frame such as PET sheet[74]. Acrylic elastomers that can attain a wide range of voltage-induced linear strains over 380% [75], and area strains more than 1000% [76, 77] were normally used. Carbon grease can be used as a flexible electrode and applied on both sides of the elastomers. The various layers of films were clamped flat until they are perfectly bonded. Once the layers are unclamped, the actuator will naturally deform and bend towards one side to achieve a minimum energy state. Bistable dielectric actuators have their limitations. For instance, Xu et al. noted that the dielectric elastomer actuator cannot have the flexibility to tune the bending angle by controlling the voltage [78]. The dielectric elastomer actuators are restrained by the structure and the maximum applied voltage. The largest bending angle achieved by the dielectric elastomer actuator was 32 degrees.

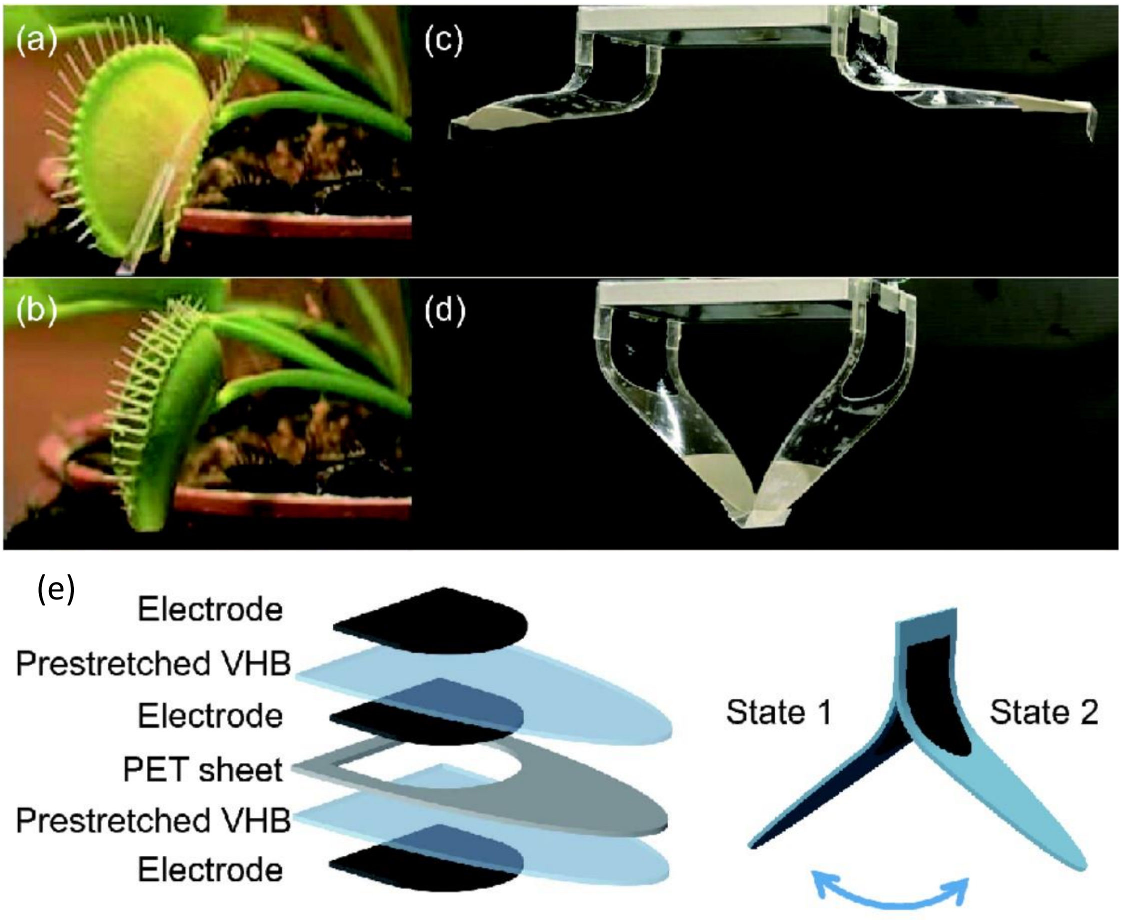


Figure 6 A Venus flytrap (a) opens and (b) closes its leaves, and the soft gripper in its (c) opened state and (d) closed state (e) multi-layer structure of the bi-stable DEMES actuator and its minimum energy states. Reproduced with permission, [74] Copyright © 2018, Science in China Press and Springer-Verlag GmbH Germany, part of Springer Nature.

Apart from dielectric actuated bistable actuators, a pneumatically actuated bistable gripper has also been developed [79]. The pre-stored elastic energy enhances the load capacity of the soft gripper. The actuator comprises 2 individual actuation chambers that are connected to a central prestressed steel shell to form bistability. The fold-mechanism of the chamber, which is fabricated using the 3D printing technique, enables the chamber to curl one side once it is inflated. The prestressed steel shell is made from the slap bracelet by yielding it in the axial direction. The straightened prestressed steel shell is then tied to the 2 individual printed chambers on both sides while they are clamped together. The performance of the bistable gripper that contains the prestress steel shell was compared to the normal dual-chamber gripper. It is found that the gripper with the prestressed steel shell is able to achieve a maximum block force of 23.5 N at 200 kPa, around 51% higher than the normal dual-chamber gripper without the prestress steel shell. The gripper with the prestress steel shell exhibits higher actuation speed, lad capacity, and bending angle. However, the returning of the pneumatically actuated bi-stable gripper to the open state takes a longer time as the pressure can only be increased gradually into the bottom chamber to transition to the straightened state.

3.1.3 Gecko-inspired adhesive

Geckos possess an array of fibrillar features on their feet which aid in producing strong adhesive force while maintaining low energy release. This unique ability inspired multiple synthetic adhesive structures though remain underdeveloped when under sheer loading conditions [21]. Gecko-inspired adhesives improve the adhesion and friction force of the gripper. The gecko-inspired adhesive is motivated by the micro- and nanostructures that are available on the toes of animals. The nanostructures are directional-they have strong adhesion when sheared in a specific direction but weak adhesion when sheared in other directions or without shear load.

Artificial materials typically used to achieve part of the gecko adhesive properties include nanostructures, isotropic stalks, and directional stalks [80]. No single material can meet all the unique properties of the gecko's toe pad. A dense network of carbon nanotubes bundles is used to form the nanostructures[81, 82]. Vertical stalks, on the other hand, consist of an array of vertically oriented flexible mushroom shape tips, which are typically made up of soft polymer[83, 84]. Both nanostructures and vertical stalks offer great adhesion but need large forces to engage and release. Directional micro-scale stalk also has an array of mushroom shape tips but is oriented at a specific angle[85, 86]. This allows for strong adhesion in a certain direction, and low force release in other directions.

There have been a few soft gripper designs that make use of the adhesives. Flexible electrostatic adhesive fingers have been developed to perform soft handling of fragile products [87]. For instance, rigid-tile gecko-adhesive grippers are well suited for handling parts with flat surfaces and have found applications in automation of the production line, and outer space tasks such as capture and release of orbital debris [53], micro-gravity mobility [88], and temporary anchoring [89]. Nonetheless, the adhesion performance of these grippers is poor on surfaces with small curvatures (few meters diameter). Dedicated flexible curved surface grippers maximize the contact area for shear-type adhesion to allow gripping at minimal surface pressure [90]. These grippers have strong gripping force at small curvatures and the gripping force is weaker when the curvatures are larger as the shear direction is not directly against gravity.

The fabrication of a gecko adhesive finger gripper involves multiple steps (Figure 7a). A mold with a microstructure surface will need to be first prepared. [80] A thin layer of silicone with a shore hardness of 30 A is then cast onto the mold. A layer of polyester mesh was added to act as the strain limiter. Silicone with lower shore hardness was added in between partially cured silicone wedges and the polyester mesh to improve the bond strength. The elastomer chamber was then added on top of the strain limiters and bonded by a layer of silicone. The difficulty in adding a layer of adhesive on the finger gripper varies depending on the mold for creating the adhesive surface. Molds are not entirely reusable, and the fabrication of the mold itself can be troublesome if conventional manufacturing techniques were used. A similar technique has been employed using polyurethane, where a negative mold of the mushroom-shaped micro-fibers was filled with the polyurethane resin [91]. The microfibers have a height of 105 microns and a diameter of 45 microns. Spin coating was used to add a 75-microns-thick elastomeric membrane and followed by adding a gripper body before the elastomeric resin was fully cured.

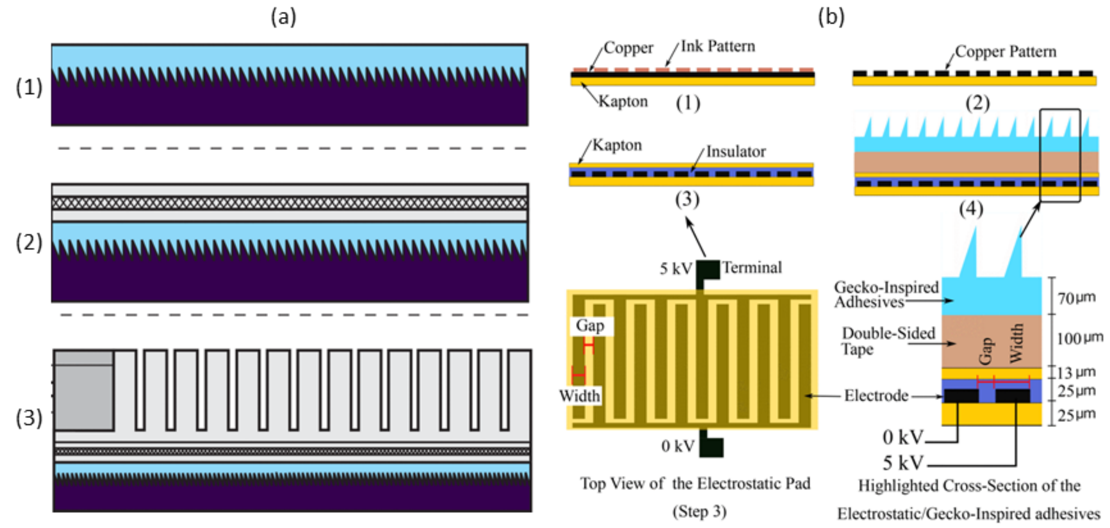


Figure 7 Fabrication process of gecko-adhesive grippers. A) 1 -Casting a thin layer of silicone onto the mold. 2- incorporating structural layers and strain-limiting layer 3- The pre-made pneumatic-actuated finger gripper is bonded to the cast silicone with structural layers. Reproduced with permission, [80] Copyright © 2018, IEEE. B) The manufacturing of the electrostatic pad with the gecko-inspired adhesives, involving electrode patterning on the Kapton sheet, etching exposed copper with ferric chloride, casting a layer of resin, and adding a layer of Kapton tape, and finally adding the cast gecko-inspired adhesives Reproduced with permission,[92] Copyright © 2020, IEEE..

Adhesion on the surface has also been created through the means of electrostatic forces. To create electrostatic adhesion, interdigital electrodes can be embedded into the inner surface of the gripper (Figure 7b) [45, 92]. The interdigital electrodes create electric fields that produce a set of capacitors on conductive substrates and polarize non-conductive substrates to produce adhesion. When combined with the gecko-inspired adhesive, the electrostatic forces induce a preload on the microstructures of the gecko-inspired adhesives. This preload forces the object to come closer to the gecko-inspired surface of the gripper and leads to a greater contact area, thus stronger adhesion. This type of adhesive is found to be effective on a broad spectrum of materials, including fabrics and rough surfaces [93].

The fabrication of the electrostatic adhesives involves multiple steps. Firstly, the patterns of the interdigital electrodes were printed on a toner transfer paper, which was then laminated to a 9-micron thick copper layer that is insulated on the other side with the Kapton sheet [94]. The exposed copper was etched away in a ferric chloride bath for 15 mins. Acetone was then used to get rid of the ink covering the copper electrode pattern. A coating resin was used to coat a 300-micron insulation layer and then a 13 micron Kapton sheet was added to reduce the spark forming.

3.1.4 Octopus arms

Unlike humans who grasp the object with their fingers or Venus Flytrap by closing both their leaves, the Octopus wraps its tentacle around the object with the help of its suckers. Even on rough surfaces underwater, the hundreds of suckers on the octopus' tentacles can form a strong grip. An octopus-like robotic arm has been developed using a flexible material such as silicone and an artificial muscular hydrostat to mimic the high dexterity of the octopus' arm. The hydrostat consists of the longitudinal cables that contract different sections of the arm and transverse muscles made of silicone that help retain the cross-sectional shape of the arm when the longitudinal cables were actuated. The arm consists of a lot of internal structures, including internal channels for the cables that are hard to be fabricated using conventional manufacturing techniques.

A cup-shaped gripper that contains micro bumps that mimic the octopus' suckers has been developed. The casting method was used in the fabrication of the cup-shaped gripper [95, 96]. The silicone mold with micro holes was first created for the gripper molding process. Silicone resin was then poured into the mold to take the shape of the gripper. Once cured, the molds were removed and a layer of the cotton filter was added to the inner surface of the gripper before adding in the glass beads with the diameter ranging from 0.7 – 1.0 mm. The presence of the micro bumps improves the adhesion [96]. The presence of a thin layer of liquid increases the adhesion by 1.8 times by filling the gap between the gripper and the object [95].

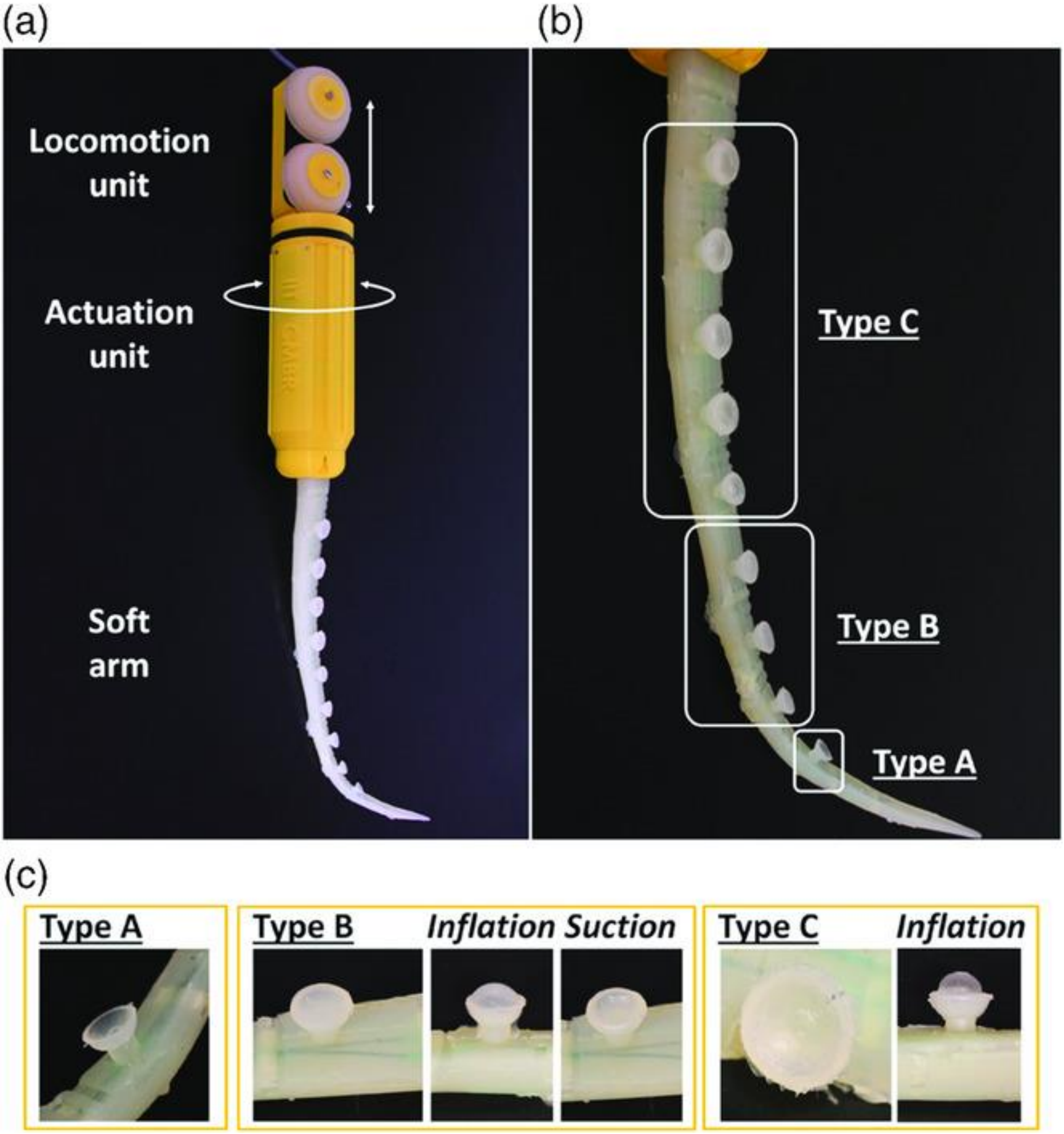


Figure 8 a) The tentacle arm gripper equipped with embedded pumps to actuate the fluidic channels, motors to actuate through cable, and linear/rotation motion control. b) image showing 3 types of suction cups on the arm gripper. c) Various suction cup designs: type A, open suction cup; type B, flat membrane-based suction cup. The flexible membrane can change shape by pressurizing and depressurizing it to allow easy release of the object. type C, the concave membrane-based suction cup. This cup, when pressurized, changes into a very dome-like structure, for easy release of the object, Reproduced under the terms of the CC-BY Creative Commons Attribution 4.0 International License. [97] Copyright 2019, WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim.

The fabrication of the robotic octopus arm with suckers involves the manufacturing and the integration of the individual components (arms and suckers) (Figure 8)[97]. For the fabrication of the robotic octopus arm, the mold for the arm was first prepared using 3D printing. The cables and rigid structures for actuation are arranged and positioned in the mold. The actuation mechanism, which contains three cables, is akin to the octopus muscle fibers that perform three separate motions: dorsal bending, ventral bending, and twisting. The pneumatic channels for the suction cups were also positioned into the mold before the casting of the silicone was performed. The casting method is also used in the fabrication of the suction cups. The molds for 3 different cup designs were 3D printed. Multi-material open suction cups were developed using a two-step casting process. The open suction cups were found to provide better adhesion compared to the membrane-based suction cups and were used at the distal part of the arm. The membrane-based suction cups were used at the center of the arm and connected in a series to a second fluidic channel. The advantages of using the membrane-based suction cups are two-fold: firstly, the membrane protects the fluidic channel from being contaminated by dirt from the environment, and secondly, it prevents the other suctions cups from experiencing pressure drop in the event when one suction cup is not properly sealed to the object.

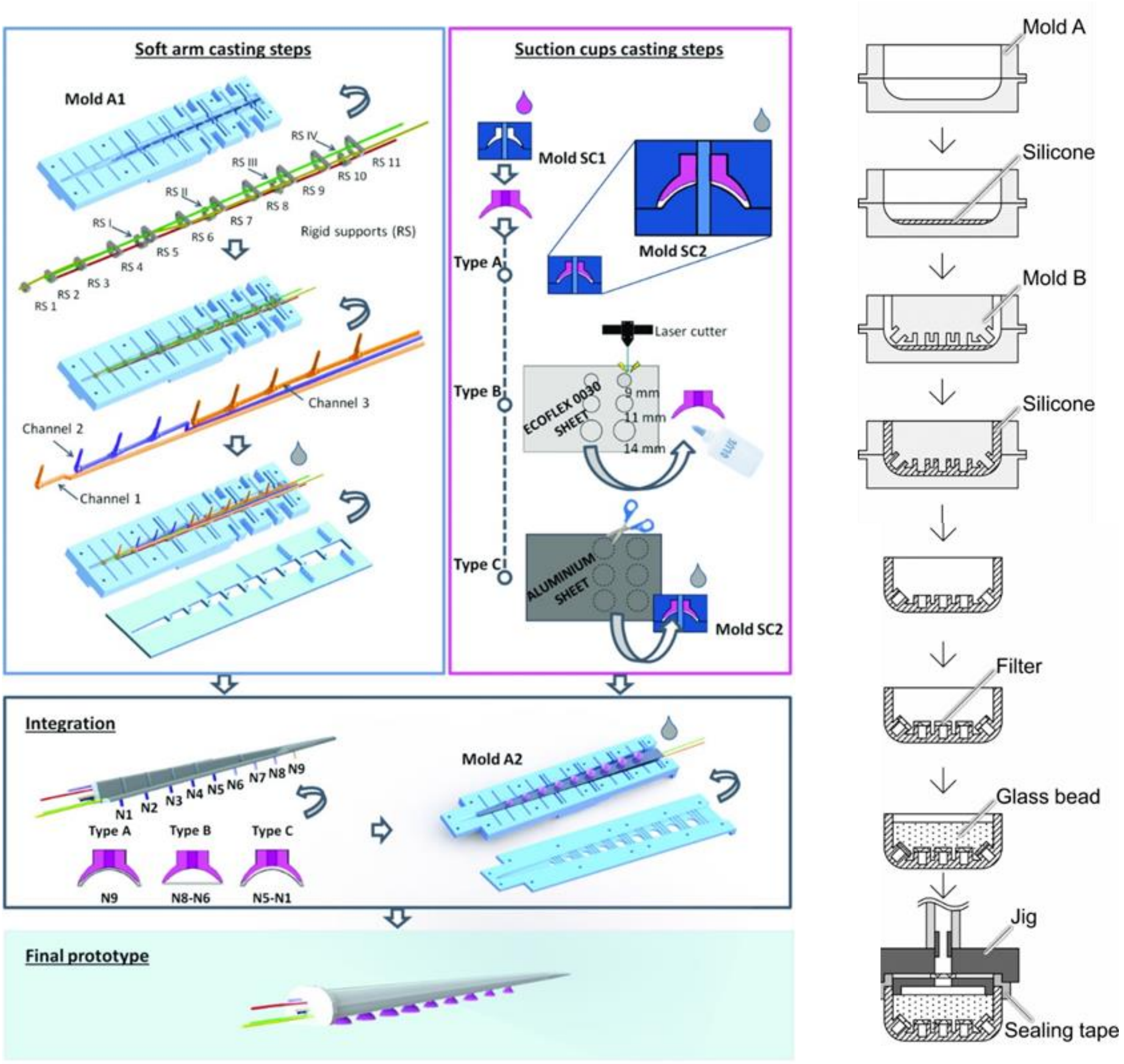


Figure 9 Development of the tentacle arm gripper with suction cups. The use of multiple molds and careful placement of the inserts such as the suction cups and channels. Reproduced under the terms of the CC-BY Creative Commons Attribution 4.0 International License. Adapted with permission, [97] Copyright 2019, WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim.

3.1.5 Twining plants

Instead of gripping objects with hands or tentacles, Climbing Plants twines around neighboring plants or pole to raise their foliage and flowers sufficiently away from the ground. This gripper is based on the stems of the Twining Plants which find support through rotating a huge diameter around a certain axis [98].

This soft gripper only requires a single pneumatic control to perform the twining which secures the target object. There are fiber optic sensors embedded into the gripper. They are high birefringence (HiBi) fiber in a Sagnac loop configuration which enables the detection of the twisting angle, the size of the object, and the occurrence of disturbance as well (Figure 10).

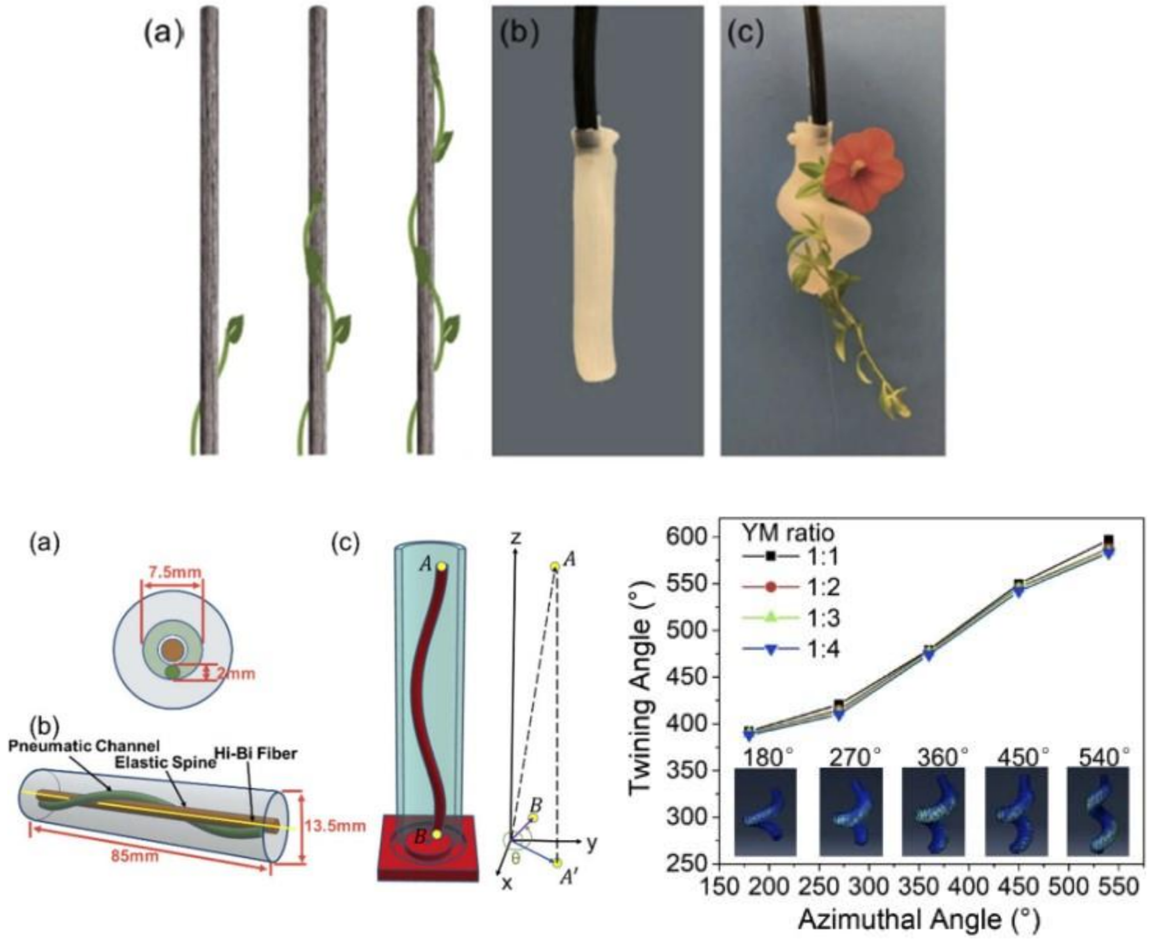


Figure 10 (a) Visual of the spiraling action in twining plant; (b) Soft spiral gripper before being actuated; (c) Actuated soft spiral gripper gripping a flower. (a) cross-section (b) 3D view of the soft spiral gripper (c) 3D-printed molds used in manufacturing the soft spiral gripper. (d) Graph of the azimuthal angle of the helical pneumatic channel versus the maximum twining angle of the soft spiral gripper with Young's modulus (YM) ratio between the gripper body and the elastic spine of 1:1, 1:2, 1:3, and 1:4. Adapted under the terms of the Optical Society of America Open Access Publishing Agreement [99] Copyright © 2020 Optical Society of America.

The fabrication of the spiral gripper involves using two 3D printed half-cylindrical molds to facilitate demolding after the silicone casting. The molds are designed such that they can be reused. The design of the pneumatic channel is critical to the performance of the spiral gripper. It was found that a smaller helical channel led to a larger twining angle for the same channel length [100]. For the fabrication of the helical channel, it was found that a 3 mm pneumatic channel wall is the optimal wall thickness as it not only provides a larger twining angle but also reduces the chance of bursting during actuation[99]. The resulting gripper was capable of performing a 540-degrees twining to firmly grasp onto a part. The HiBi fiber, which was embedded in the central spine to avoid delamination during actuation, was able to provide good sensitivity in the twining angle detection (0.03 nm/degree).

Shape Morphing of Programmable Polymer–Paper Bilayer Composites are able to achieve both helical and spiral deformations[101]. Helical deformation in a single structure was achieved by taking advantage of the anisotropic properties of the 3D printed filament, the printed Polyethylene (PE) layer serves as the anisotropic layer where all the PE filaments are printed with a determined angle in parallel to the length of the paper substrate.

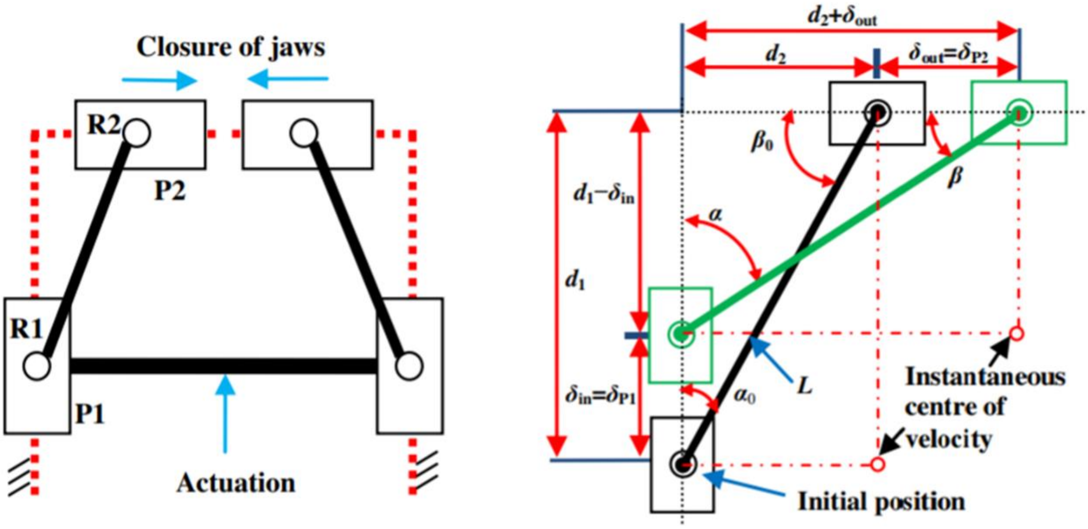
In short, the design of the bio-inspired soft grippers varies in terms of material usage, actuation mechanism, and sensing capability. All these design considerations will not only affect the final performance, but also the manufacturability of the soft grippers.

3.2. Compliant

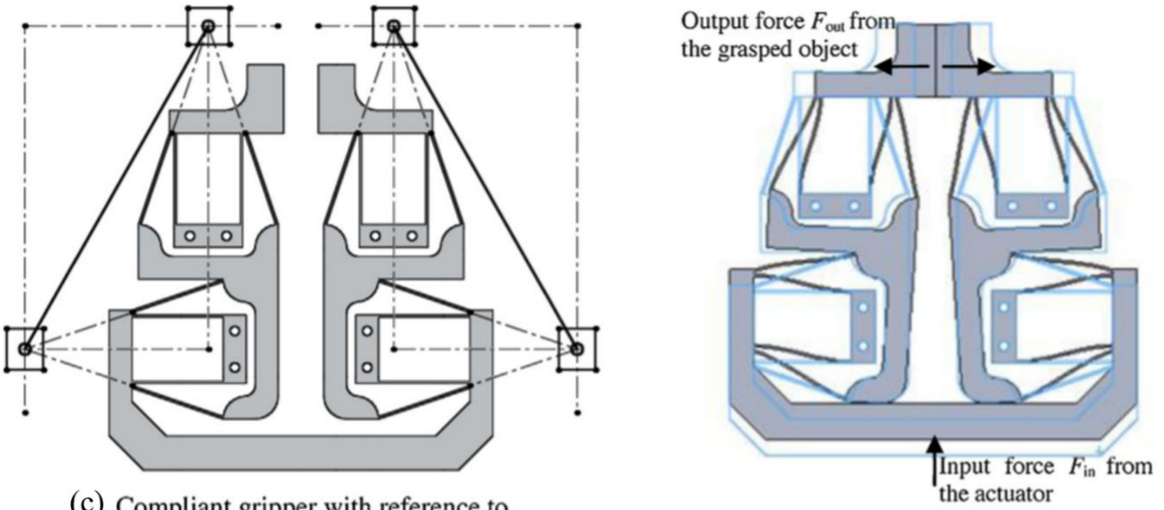
A compliant mechanism is a mechanism in which at least part of its mobility comes from the bending of the flexible element, not just purely from the rotating joint as in the kinematic mechanisms. By minimizing or eliminating the need of including joints in a mechanism, it greatly decreases the wear and tear of parts and thus increases the durability of the mechanism. In contrast to rigid mechanisms, compliant mechanisms generally have an added advantage that enables the compliant members to be adaptive in a limited range during operation, and can also minimize potential damage to the items being gripped. Compared to using soft material, compliant design can generate higher force and it has a higher response time in general. Compliant Mechanisms are known to be difficult to design and manufacture due to the complexity of the part. Recent advancement in 3D printing has enabled the creation of geometrically complex compliant mechanisms. By using a compliant mechanism for a gripper, the gripping force would be largely dependant on the flexibility of the material thus by selecting the correct material and appropriate design, a soft gripper using a compliant mechanism can be used to achieve targeted gripping force.

3.2.1 Kinematic compliant mechanisms

In the conventional kinematic design, links and joints are used to achieve force and motion transmission (Figure 11a,b). In the kinematic compliant design, the rotational motion of the link is realized by the elastic deformation of the material (Figure 11c,d). The kinematic gripper is normally actuated using linear actuators like the stepper motors. As the design is normally 2D, the sensors can be incorporated easily. Another advantage of the kinematic compliant gripper is that it requires minimum assembly compared to conventional kinematic grippers which have links and joints. As it has a 2D design, it can be fabricated using a laser cutter. However, one downside of using the laser cutting technique to fabricate grippers is that only monolithic gripper designs can be produced, meaning that the grippers have the same material properties throughout the grippers. This reduces the design freedom. More advanced gripper designs have been fabricated taking advantage of the multi-material fabrication capability of the 3D printing techniques. For instance, a compliant gripper that consists of both soft TPU and rigid PLA was developed to increase the compliance and friction of contact as well as maintain the advantage of hard material sections [102]. Bayesian optimization was used to obtain a set of design parameters for the optimum success rate of grasping and the ability to bring the object to the center of the gripper. The optimized multi-material gripper was found to have higher success rates (90-100 %) in grasping objects like a tennis ball, rope, and pen compared to its single material counterparts (30-85%).



(a) 2-PRRP mechanism (b) PRRP mechanism



(c) Compliant gripper with reference to its rigid-body kinematic mechanism (d) Compliant gripper in deformation

Figure 11 A 2-PRRP rigid-body kinematic mechanism A compact large-range compliant gripper. Reproduced with permission, [103] Copyright © 2016, Elsevier.

Another point to take note of is that the jaws tend to be rigid, which means it is less conforming to the object.

3.2.2 Topology optimized compliant mechanisms

Topology optimization (TO) is a mathematical approach that optimizes the distribution of the material within a given design space, for a given set of loads and boundary conditions such that the resulting distribution meets a specified set of performance goals with a lesser amount of material (Figure 12). In other words, the shape of the final gripper design is determined by the initial design boundary and the loading conditions. For instance, the Ant Search algorithm, where any variable related to topologies such as the element length, width, and thickness can be optimized, was proposed for the generation of fully compliant mechanisms [104]. Another work involved the use of a modified SIMP approach to optimize the pneumatic-actuated soft gripper [105]. In that work, homogeneous material and linear model were used. The same research group also used TO in the design and development of multi-material compliant gripper [106], which poses a significant challenge to fabricating it using conventional fabrication techniques. In general, TO results in complex shapes that are hard to manufacture using the conventional manufacturing process, hence, it is common for topology optimized compliant grippers to be fabricated using 3D printing techniques, taking advantage of their freeform printing multi-material printing capability [106-109]. For instance, Zhang et al. created a multi-material soft gripper by using both conventional moulding approach and the material extrusion 3D printing technique. The soft material layers made of silicone was moulded into a simple regular-shaped parts, where the optimized hard layer was fabricated using thermoplastic elastomer via the material extrusion 3D printing technique. The combination of the fabrication technique allows reliable multi-material gripper to be fabricated at a relatively low cost.

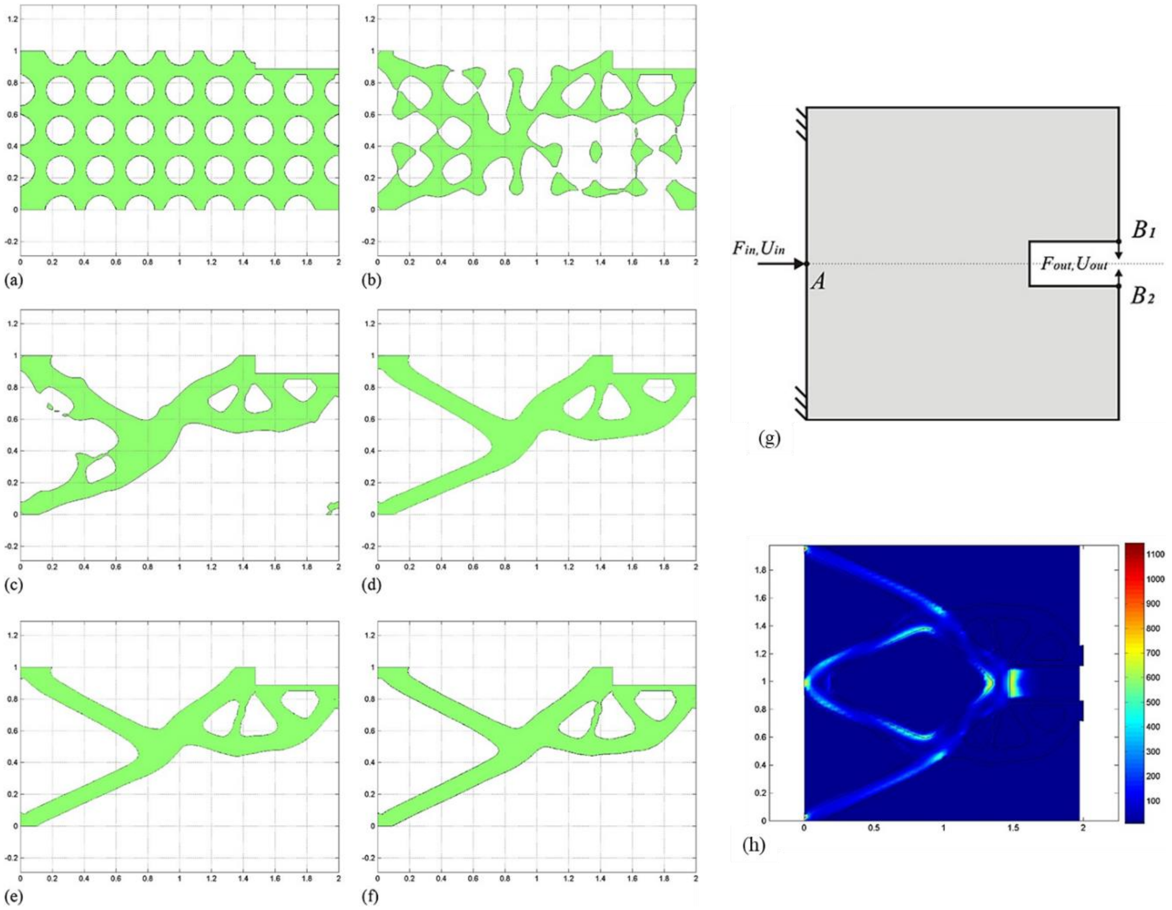


Figure 12 The intermediate designs of the push gripper using Q2: (a) step 1, (b) step 50, (c) step 100, (d) step 200, (e) step 350, and (f) step 450. The final design of the push gripper using Q2: (a) topology result, and (b) Von-Mises stress distribution. Adapted with permission, [110] Copyright © 2012 John Wiley & Sons, Ltd.

Compared with rigid mechanisms, a potential downside of deploying compliant mechanisms is that the mechanical advantages of the compliant gripper are usually smaller than those of rigid mechanisms of the same sizes. Put differently, for the same given input force, the output force of a compliant mechanism is usually less than the output force of its rigid counterpart.

3.2.3 Origami

Robotic origami gripper is another type of gripper design, in which stiff surfaces linked with flexible hinges to create targeted 3-D shape arrangements [111, 112] by self-folding, and varying stiffness modes by collapsing the structure [113], locking some of the hinges [114], or through variable stiffness material joints [115]. For example, a compliant origami mechanism that has both large energy storage and self-locking properties is inspired from the wing vein in ladybird. The compliant origami structure actuates within 116 ms and has a load-bearing capacity of 210 grams, which is 150 times its weight[116]. Another example would be a study done on “Bioinspired dual-stiffness origami” (Figure 13)[117]. This study prototyped a compliant origami inspired by an insect wing that only folds when a certain threshold of the load is applied. This is achieved through the connection of rigid tiles with pre-stretched elastomer membranes at key positions in the structure. “Bioinspired dual-stiffness origami” seems promising as the study managed to develop a compliant gripper using their dual-stiffness origami as a basis. The compliant gripper can act like a rigid gripper below a force threshold, which can be tuned by varying the material properties of the pre-stretched membrane and the folding patterns. When the force threshold is exceeded, the origami acts like a soft gripper and is able to conform to the part. The dual-stiffness characteristics is useful to allow rigid grippers to soften when handling delicate parts.

They are normally cable-actuated and can have a fast response. With that said, an innovative reconfigurable origami suction gripper, actuated by shape memory alloy and vacuum, that incorporates the flexibility of the origami folding with the conformity of soft materials to overcome the shape compliancy for suction grippers. The suction gripper has a load-bearing capability of 5 N and is capable of lifting slender objects such as a pen [118].

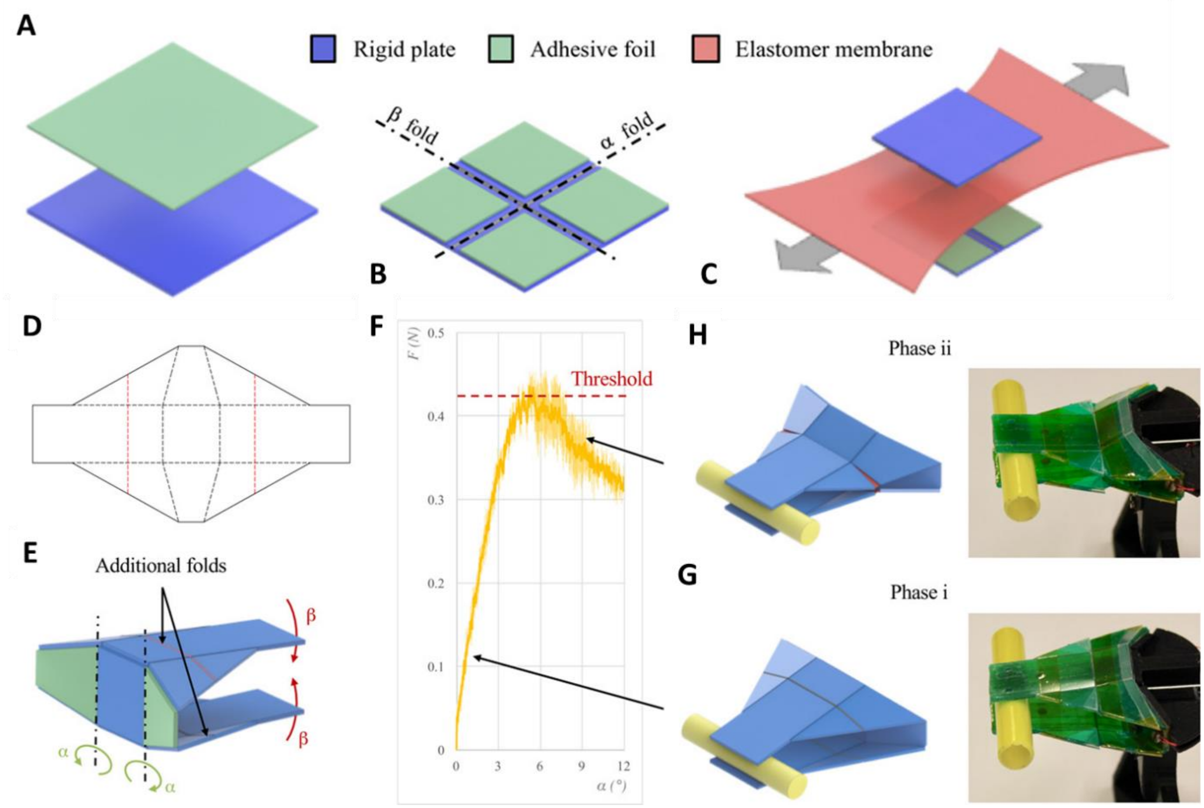


Figure 13 (A) The rigid plate and the adhesive foil are joined together to form a composite sheet. (B) The folding pattern is engraved onto the composite sheet using a laser (C) a prestretched elastomer membrane is sandwiched between two composite sheets. (D) The modified Oriceps crease pattern. (E) The grasping motion of the compliant origami (F) graph of grasping force F with respect to the input angle α. (G) The origami gripper in the rigid configuration firmly holding an object. (H) The origami gripper in the soft configuration holding an object without overloading it. Adapted with permission, [117] Copyright © 2018, The American Association for the Advancement of Science.

An origami-inspired fluid-driven artificial muscle that comprises airtight skin wrapping around a foldable skeleton and a fluid medium (Figure 14) [119]. The artificial muscle shrinks at low pressure. The skeleton will be retrained by the skin when the artificial muscle shrinks. This forces the fold lines to be compressed when the fluid is drawn out, and thus the shape-changing of the gripper. Two types of skeletons have been developed. The first skeleton is the self-folding of a plastic skeleton. The fabrication of the self-folding skeleton is complicated as it is a multi-layer structure that requires cutting of PET structural materials into specific shapes and bonding them with a layer of heat-shrunk PVC plastic. A high-temperature Kapton sheet was bonded to the laminate structure such as the edges of the adjoining structural materials coming into contact to fold into a 3D shape. An airtight fabric skin made of a TPU-coated nylon sheet was then used to form the airtight layer for the actuation. The second skeleton is the silicone rubber skeleton. The fabrication of the silicone rubber skeleton is much easier, as it involves 3D printing of the molds for the skeleton and the casting of the silicone rubber skeleton. Latex rubber balloon skin was then used to wrap the rubber skeleton. It was found that the self-folded skeleton gripper was able to achieve around 30 N holding force while the rubber skeleton gripper was able to achieve 120 N[120].

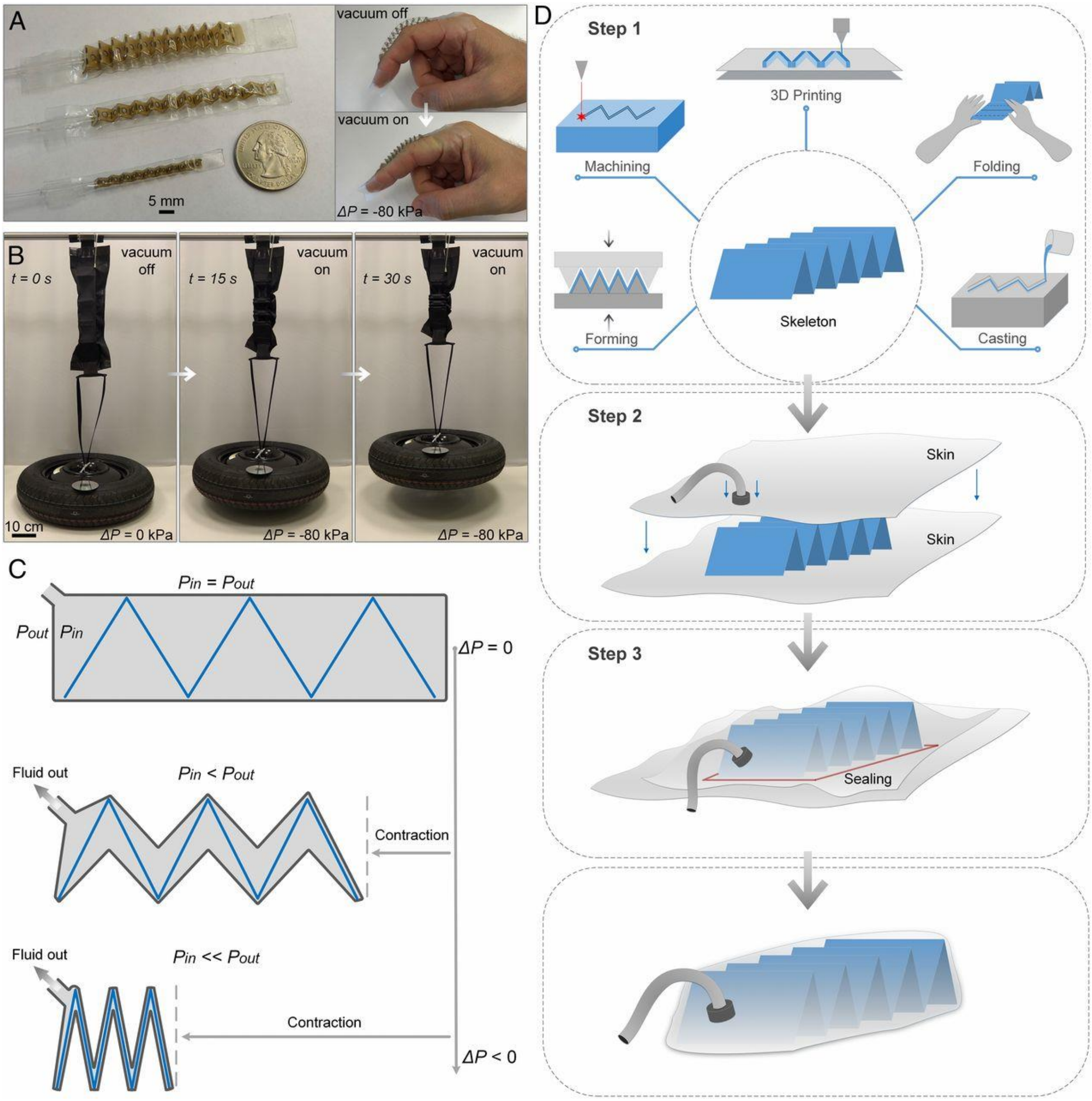


Figure 14 Development of origami-inspired fluid-driven artificial muscle. (A) The contraction of the actuator when the vacuum is actuated. (B) Demonstration of the high lifting power of the artificial muscle by lifting a car wheel weighing 22 kg. (C) Working principle of the actuators. Contraction is mainly driven by the tension force of the skin. This force is produced by the pressure difference between the internal and external fluids. Withdrawing fluid from the actuator will temporarily decrease the internal pressure. (D) Manufacturing workflow (1) skeleton construction, (2) skin preparation, and (3) fluid-tight sealing. Reproduced with permission, [119]

3D printing technologies have also been used for the development of origami grippers by taking advantage of the 3D printing polymers that exhibit shape memory effect. For instance, polylactide (PLA) have been known as the low cost and most accessible polymer that is easy to print and program[121]. The origami gripper was printed flat and contains two portions, which is the hinge and the panels. The panels do not experience any significant bending and deformation during the programming and shape-recovery steps. The origami gripper can then be folded into the pyramid shape by bending the hinge during the programming step. The programming step involves putting the as-printed flat origami gripper into the hot water bath with temperature of 65 °C for 60 s, and thereafter folding the gripper into the pyramid shape. The specimen were then removed from the hot water bath and allowed to cool down to room temperature while continuing to exert external load to maintain the pyramid shape. To recover to the flat shape, the gripper needs to be heated beyond its glass transition temperature. To date, a lot of 3D printed complex origami structures such as the active sandwich structures that have different folded states [122] could see potential in the gripper applications.

However, scalability is an issue in the origami design. It is known that the gripper's mass will increase at a higher rate compared to its stiffness due to the square-cube law. Although it can lift some items, it lacks the carrying capacity of other similar-sized grippers. Also, it is susceptible to fatigue caused by repeated folding and unfolding at the joints. Not to mention that it is also hard to manufacture given that it has multiple hinges and joints.

4. 3D printing techniques for the fabrication of grippers

3D printing techniques have been used to create soft grippers with novel designs that are hard to be manufactured using conventional manufacturing techniques. In this section, various 3D printing techniques will be reviewed in terms of the working principles, their advantages, and disadvantages concerning the fabrication of soft grippers. Figure 15 shows schematics of various 3D printing techniques.

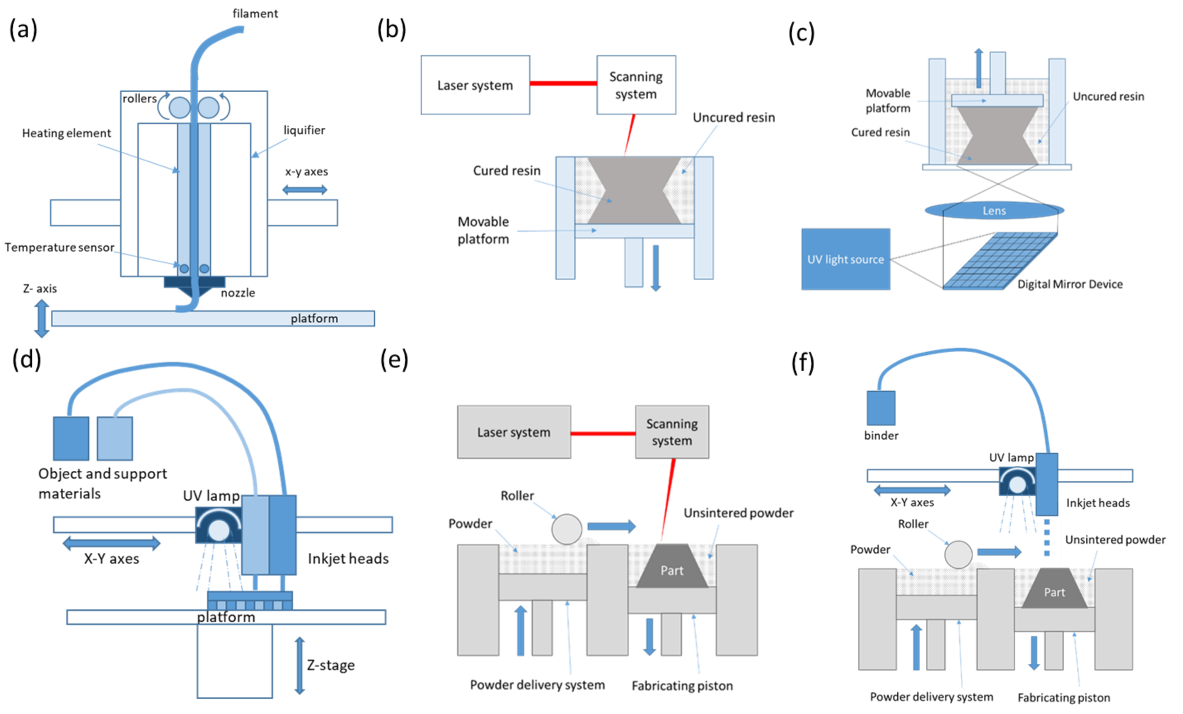


Figure 15 Schematics of various 3D printing techniques. a) material extrusion b) Vat-photopolymerization (micro-stereolithography) c) Vat-photopolymerization (DLP) d) material jetting e) powder bed fusion f) binder jetting. Reproduced with permission, [123] Copyright © 2017, Elsevier.

4.1 Material Extrusion

One example of material extrusion is fused filament fabrication (FFF). In FFF, parts are manufactured through the selected deposition of the molten plastic via a moving printhead [124]. A huge benefit of the technique is that a broad spectrum of thermoplastics can be used through this process, ranging from standard thermoplastics such as polylactic acid (PLA) [125, 126] and Nylon [127] to aerospace-grade Ultem^{TM} thermoplastics [128], elastomers such as thermoplastic polyurethane (TPU) and composite materials [129-131]. Figure 15(a) depicts the illustration of the FFF technique.

Another advantage of this technique is that it can be easily scaled into a multi-extruder system, allowing each extruder to extrude a different material to achieve multi-material printing. Apart from that, various soluble support materials such as polyvinyl alcohol (PVA) or high-impact polystyrene (HIPS), which are soluble in water or dipentene, respectively, have been developed for easy removal of the support structure [132]. As the use of support structures is sometimes unavoidable and is required in regions that are hard to reach, the ability to process soluble support material becomes important. It is especially the case for the fabrication of pneumatically actuated soft grippers because they need to be fabricated in one piece to ensure they are air-tight, but overhanging features are bound to exist in such designs. Using soluble support materials would eliminate the support removal problem in the hard-to-reach region.

Due to its ability to process multiple types of materials, the material extrusion technique has also been used to print shape memory polymers, which change shape or properties in the presence of external stimuli such as heat, vibration, illumination. For instance, the shape-changing effect of PLA, which changes phase at its glass transition temperature (60°), has been used to create robotic grippers that are stimulated by temperature [133].

Printing materials as soft as silicone can be problematic using the material extrusion technique. The soft nature causes the soft materials to deform under their own weight, resulting in dimensional accuracy issues and difficulty in printing tall structures. A few methods have been proposed to overcome this issue such as printing the soft materials in solution with equivalent densities [134-136] and having sacrificial support structures [137] during the printing process.

Another limitation of the material extrusion technique is that the printed part tends to have a higher level of porosity. A typical porosity level of an FFF-printed part is in the range of 2-10%, where the majority of the voids are formed in between the roads of filaments [138, 139]. High porosity levels are not desirable in soft grippers as high porosity reduces the fatigue resistance, which leads to a short lifespan of the grippers. The high porosity level would also increase the permeability of the printed part, which is not ideal for pneumatic actuated grippers. This, however, can be circumvented by proper optimization of the print parameters. It is found that having a negative raster air gap can significantly reduce the porosity of the printed parts.

4.2 Vat Photopolymerization

Vat photopolymerization printing utilizes light in the UV spectrum to cure UV-sensitive fluid resin in a layer-by-layer fashion [140]. There are two types of Vat photopolymerization setups, namely the micro-stereolithography and the digital light projection (DLP) as shown in fig. 9 [141]. In the micro stereolithography, the direction of the laser beam is controlled by the computer and the laser will scan through the resin bit by bit where illumination is required according to the CAD model. Higher resolutions can be achieved compared with DLP. In the digital light projection (DLP) system, a digital mirror device (DMD), which comprises an array of hundreds of thousands of mirrors that can be switched independently, is employed. By manipulating the mirrors of the DMD, the pattern of each layer can be reflected on the resin so that a complete layer can be polymerized at once. The printed part is not fully cured and post-printing heat treatment is needed to fully cure the part.

Stereolithography (SLA) is known for its ability to create parts with high dimensional accuracy. Parts fabricated using SLA normally have very good surface finishes, owing to its ability to print material at a layer thickness as low as 10 microns and a horizontal resolution of 50 microns [142]. SLA parts also exhibit a low porosity level (0.02-1%) [143], which is good for a pneumatic-actuated soft gripper that requires low permeability. Unlike the FFF technique that uses thermoplastics, the SLA techniques prints thermoset polymers[144]. Although there are various types of resins with different hardness and strength, the material choice of this technique is not as wide as the material extrusion technique. As the SLA materials are UV-sensitive, prolonged exposure to sunlight degrade the mechanical properties and appearance of the SLA-printed parts [145]. The mechanical properties of the SLA-printed poly methacrylate material are known to be adversely affected by the environmental aging with high-low temperatures (50 °C and -20 °C) cycles [146]. These SLA materials are also known to creeping, meaning that they will deform under constant load[147]. This would cause repeatability issues in the actuation motion of the soft grippers.

Another limitation of this technique is the inability to process multiple materials during the printing process. Although several research works on multi-material printing have been reported that involved changing of vats [148, 149], there is hardly any commercially available printer that can perform multi-material printing. This would certainly limit the design flexibility, especially in the creation of multi-stiffness gripper structures. As most SLAs can only process single material, the support structure is also printed using the same material as the model structure. This makes the support removal hard as the support structures are normally removed mechanically. Internal support structures can be hard to remove and would require special tools to remove them completely. The problem of support structures removal can be overcome by the careful design of the internal structure to avoid overhanging features.

To date, SLA is used to print connection rods and claws of the kinematic grippers [150], components of compliant grippers [151], and a fully printed topology-optimized gripper actuated by servo motor [152]. Apart from direct fabrication, SLA has also been used to print soft gripper mold patterned with small caves array to improve the gripping adhesion [153].

4.3 Material Jetting

Material jetting operates in the same way as inkjet printing. Contrary to inkjet printing that jets ink droplets onto paper, material jetting jet layers of UV curable fluid onto a print bed [154]. Figure 15(d) illustrates the schematic of the material jetting technique. This technique makes use of the soluble resin for the support structures in which the support structures can be removed easily by mechanical agitation or soaking in an ultrasonic solution bath. Unlike stereolithography, post-processing is not required for the printed parts as parts are fully cured once the print is done. Due to the multi-nozzle printhead, one advantage of material jetting is the capability to incorporate different material compositions into a single model to realize functionally graded material or structure[155], giving the users the design flexibility to achieve a more optimal design. For instance, the pressure sensitivity of the 3D printed soft gripper was improved by 50% through the fabrication of soft patterns (FLX9840) on hard material (RGD8530), taking advantage of the multi-material printing capability of the material jetting printing technique [10]. Fabrication of soft actuators with periodic inelastomeric stiff inserts has also been attempted. The periodic stiff patterns within the soft gripper change the mechanical behavior and enhance the applied maximum load without degrading the flexibility of the gripper [156].

The material jetting technique is also capable of processing shape memory polymers. A variable stiffness composite actuator with the ability to retain and recover its shape has been developed [157]. The stiffness of the SMA-actuated grippers is controlled by varying the temperature of the printed shape memory polymers via joule heating.

Material jetting parts exhibit close to zero porosity, making it ideal for the fabrication of the pneumatic-actuated soft grippers. However, similar to SLA parts, inkjet printed parts suffer from the creeping problem. For instance, the stress of the Polyjet DM9895 dropped from 2.7 to 1 MPa in less than 10 seconds in the stress relaxation test [158]. It is also known to have a slow recovery rate from high loading conditions [159]. Nonetheless, it is one of the widely used 3D printing techniques used to fabricate soft grippers.

4.4 Powder Bed Fusion

In power bed fusion, parts made of thermoplastics, metal, or ceramics are fabricated by the scanning of laser to selectively melt and solidify each successive powder layer [160]. Polymeric materials are normally processed using selective laser sintering (SLS). The working principle of SLS is illustrated in fig. 10. A Galvano mirror is used to guide the continuous wave carbon dioxide (CO_2) laser with an average power of several 100W to kW laser beam to selectively scan on the layer of powder based on the CAD file. Although various materials have been attempted, the printing of SLS parts is mainly restricted to single material printing, making it only suitable for the fabrication of monolithic grippers, or components of kinematic grippers. Nonetheless, composite feedstock, a mixture of magnetic Nd2Fe14B and thermoplastic polyurethane powders, has been developed and also used to create magnetic-responsive grippers[161]. A functionally graded compliant gripper has also been developed by changing the composition of the composite feedstock at different print layers to make the upper part of the compliant gripper stiff to grasp the object while the lower part flexible to efficiently generate the motions under the action of applied forces[162]. This printing method requires constant changing of feedstock materials, which is typically done manually. Unlike, other printing techniques, the entire layer of the powder bed, including the unsintered powder functions as the support for the successive powder layers and the overhanging portion of printed parts [163]. Hence, it is not required to print physical support structures that are hard to remove. The unsintered powder can be simply removed by some mechanical agitation. Another limitation of the SLS technique is the porosity level of the printed part. The porosity level typically ranges from 4-10%, making it permeable to air. Despite this, this technique has been used to create various pneumatic soft grippers [164, 165], topology optimized vacuum gripper [166], and components of the soft gripper [167].

4.5 Binder Jetting

Binder jetting is a category of 3D printing techniques that combines powder bed fusion and the material jetting technique. In binder jetting, the feedstock material in the powder form is coated into a layer and selectively joined into the targeted layer pattern with a binder, which is usually a polymeric resin [168]. As the printing takes place, parts of the layers are bonded together, leaving a box of powder with a binder arranged in the 3D shape of the targeted part geometry. Heat treatment may be used during the printing to partially cure the binder to form the “green” part. The green part will need to be further post-processed after being removed from the build platform. Post-processing treatments such as sintering or infiltration are required to strengthen the green part.

One advantage of binder jetting is that, due to the adoption of the inkjet printing technique for the binder resin, the binders can be premixed with different coloring to enable multi-color printing.

Like powder bed fusion, binder jetting has been used to process ceramics [169], metals [170], and polymers [171]. Although, in theory, the binder jetting is compatible with any powdered material, the material variety is limited as a correct combination of the powder material and the binder resin is required for good printing. For instance, the bulk density of the polymethyl methacrylate increased by 25% when the composition of the aqueous binder that contains maltodextrin and polyvinyl alcohol (PVA) increased from 10 $_{vol}$% to 60 $_{vol}$% [172]. Polymers such as polyglycolic acid (PGA), polylactic acid (PLA), polycaprolactone (PCL), and polyethylene oxide (PEO) have been printed using an appropriate binder[173]. The relatively limited material choice in binder jetting restricts the design flexibility in the design of the grippers. The binder jetting technique is also restricted to single material printing, making printing of functionally graded grippers almost impossible.

As in powder bed fusion, as the powder layers act as the support for the successive layers, the printing of support structures is not required. This is ideal for gripper designs that have intricate internal and overhanging features, such as the internal channels for the pressurized air or the cables. In comparison with the powder bed fusion, the binder jetting can produce fully dense parts, which have low permeability and good water-tightness [174].

Several gripper designs have been developed and fabricated using the binder jetting technique, which includes the components of the gripper[175] and fully printed tendon-driven grippers [176].

In brief, each 3D printing technology has different features that the gripper designers take advantage of to fabricate grippers. Table 1 summarizes and compares the key features of the printing techniques such as the porosity level, ability to print multi-material, ease of support removal, and its ability to print smart materials. Generally, all 3D printing techniques can be used to produce soft grippers owing to their ability to process elastomers. The selection of the fabrication techniques can be recommended based on the soft gripper requirements and the actuating mechanism. For instance, if multiple materials are involved in the gripper designs, material extrusion or material jetting are recommended. If pneumatic actuation is used for the soft grippers, fabrication techniques such as powder bed fusion and binder jetting that can produce low porosity parts are recommended.

Table 1 Summary of various 3D printing techniques for the fabrication of soft grippers

	Material Extrusion	Vat photo-polymerization	Material Jetting	Powder Bed Fusion	Binder Jetting
Multi-material printing	Yes (depending on # nozzle)	Possible. No commercially available printers	Yes (wide range)	no	no
Ease of support removal	Easy– soluble support	hard	Moderate –wax support slightly soluble	Easy	Easy
Porosity	1.6-10%	2.10-2.95%	~0%	4-10%	<1%
Smart material	PLA, TPU, PEMA, PVA	· PDMS · Rigid part	A composite of SMP fibers in an elastomeric matrix, A composite of wood-derived fibrils	Nd2Fe14B and thermoplastic polyurethane	-
Pros	• High strength material such as Ultem is available • Wide range of thermo-plastics	• Able to fabricate fine feature size • Good surface finish • Insignificant stair-stepping effect	• Able to mix materials to create functionally graded parts with multi-material printing • Able to print fine features • Good surface finish • Insignificant stair-stepping effect • Fast printing process	• Ability to print parts with good mechanical strength • Large build area • Relatively low cost • Do not require printing of support structure	• Do not require printing of support structure • Minimal distortion of parts as minimum heat is required. • Fast printing process
Cons	• Slow printing process • Obvious stair-stepping effect in the z-direction • Poor surface finish compared	• Poor stability of the SLA material resulting in permanent deformation of parts under load • Single material printing	• Slow recovery rate from high loading condition • Creeping is prominent	• Rough surface finish	• Low part strength (typically lower than that of the powder bed fusion)

	to polyjet and SLA				

5. Sensors for soft grippers

There has been growing interest to discover the potential application of sensors for robotic use especially for the unstructured and changing environment, particularly with the use of soft grippers. The role of sensors is integral for enabling soft grippers to respond to this environment. Sensors are an integral part of smart grippers as haptic feedback signals resulting from the response to stimuli can be obtained, and appropriate commands can be given to improve the handling of objects. With such compliant and adaptive soft grippers, it is crucial that contact forces and feedback are detected during task activities such as manipulation and assembly. There is a need to have flexible sensors which would be able to attach and integrate to these soft grippers. Various reviews have been made for these soft sensors, ranging from materials used to fabricate[177], fabrication methods such as 3D printing [178], and applications [179]. There has been an increasing development of flexible sensors with many tactile products available commercially which provide multi-modal sensing capabilities for structured and unstructured environments [177].

These flexible sensors on soft grippers provide information such as geometrical shape, weight, location of objects to carry out their tasks. Mechanical parameters such as strain, force, and pressure are used to provide the detecting capabilities of these sensors.

For these sensors to be applied to soft grippers, these sensors must be at least flexible and stretchable without adding significant stiffness. Ideally, these sensors are required to have high sensitivity, high spatial resolution, and a high degree of accuracy with linearity and minimal hysteresis. Practically, there is a compromise between sensitivity and mechanical resilience. For the sensors to be successfully integrated into these grippers, they must be fabricated easily.

These sensors can be classified based on their transducer mechanism see in Table 2; resistive, capacitive, piezoelectric, magnetic, and optical. Sensors’ critical parameters are stretchability and hysteresis, sensitivity and linearity, response time, and durability [179]. As these sensors are practical and non-ideal, there are issues of non-linear behavior, sensitivity to temperature or electromagnetic noise, and hysteresis, among others.

Table 2 Overview of sensors

Type of Transducer	**Mechanism**	**Examples**			
		Material	**Sensitivity**	**Range**	**Features**
Resistive/ Piezoresistive	Detect resistance changes due to deformation, pressure	Multi-walled carbon nanotube (MWCNT)/polymer composite [180]	~0.5 N	0 - 50N	Noise filters using FIR (Finite Impulse Response) filters and IIR (Infinite Impulse Response) filters
		Carbon fibre polymer composites (CFPC) and thermoplastic Polyurethane (TPU) films [181]	Gauge Factor: 85,000	0 - 100kPa	-
		Gallium-based liquid [182]	0.45 %/ kPa	0 - 900kPa	Operates at 3.6Hz
Capacitive/ Piezocapacitive	Detect changes of the electric field of the capacitor due to deformation	Microstructured elastomers [183]	0.20 / kPa	0 - 22kPa	Signal-to-Noise: 8
		Conductive graphene nanoplatelets (GNPs) or Carbon nanofibers (CNFs) [184]	0.85 ± 0.03 pF/ kPa	0 - 12kPa	Noise of 0.02pF
Piezoelectric	Detect changes in voltage from the internal polarization due to external stress	Poly-vinylidene difluoride film with a micro-structured jamming layer [185]	0.09 Vm/ N	0 - 40kPa	-
Magnetic	Based on Hall-effect, detect changes in the	Hall Effect sensors orthogonally placed at the base of a silicon	Error of less than 5%	0 - 25N	Output signal filtered

	magnetic field due to the displacement	rubber hemisphere with neodymium permanent magnet [186]			using a 500 Hz cut off frequency low pass and an average filter
Optical	Detect the shift in wavelength due to the stretching and bending of the fiber optic	Strain sensor based on the photoelectric effect[187]	Gauge Factor: 1050	Strain: 800%	Signal-to-Noise ratio: 60dB
		Optoelectronic printed circuit board (PCB) [188]	0.018 V/ N	0 - 15N	Signal-to-Noise: 5–6
		Fiber Bragg Grating (FBG) [189]	Normalised root mean square error: 0.75%	0 - 8N	-

With most mechanisms due to the change in deformation (strain), it can be seen that the resistive-based sensor are more common [187, 190]. Alternatively, there are materials such as artificially innervated foam (AiFoam) [191] which can operate in both piezoresistive and piezocapacitive by embedding 3D electrodes within its foam compositive.

These sensors have their own performance characteristics which should be assessed for the tasks that the soft grippers will be carrying out. A way to evaluate these sensors in grippers, the performance of an object recognition task based can be measured on deep convolutional neural networks (DCNNs) [192].

One category of flexible sensors is tactile sensors. For example, anthropomorphic robotic grippers with commercial tactile sensors can handle delicate shapes and size objects [193]. In this case, surgical robots use tactile sensors to provide haptic feedback, allowing the surgeon to better carry out their tasks together with visual control. Additionally, a skin-inspired highly stretchable, and conformable matrix network (SCMN) allows additional sensing functionality such as temperature, in-plane strain, humidity, light, magnetic field, pressure, and proximity [194].

Besides tactile sensors, there are commercially available pressure and flex sensors integrated into soft grippers. For instance, a Pneumatic soft sensor (PSS) [195] has a pressure sensor designed onto a silicon rubber sensing body. The pressure against contact force is correlated for PSS to be used as a contact force sensor. With the silicon rubber body, it has good deformability and can be added to the gripper easily. Flex sensors are readily available commercially for easy integration on soft pneumatic actuators within its strain limiting layer. It can be embedded in the fingers of soft grippers to detect and estimate the grasped object size, the contact with the target, and grasp type [196].

Soft grippers with these sensors are highly adaptable to the shape of objects and teleoperation with haptic feedback allows for complex work to be performed such as grasping and handling fragile items remotely [197].

6. Design and Fabrication of soft sensors for soft gripper

The integration of sensors into soft grippers presents several constraints and challenges such as the material selection for the sensors and the fabrication of the sensors. For instance, the materials used for the sensing element of the sensors must be carefully selected to ensure that they have the material properties (eg. Young's modulus and elongation) that match with the base structure of the soft gripper to ensure its functionality and reliability [198]. However, most commercial sensors use sensing elements that are made up of conventional metal conductors that normally have high stiffness and poor elongation property. Various efforts have been made to make these conventional materials compatible with soft grippers, which includes making them into thin metal films or converting them into nanomaterials[199]. The former involves the use of thin-film deposition techniques such as electron beam vaporization, together with stretchable thin-film designs such as buckled film, serpentine circuit, and kirigami that reduce the stress when the material is flexed [200-204], whereas the latter usually involves the mixing of the conductive nanomaterial with a stretchable matrix material to form the electrically functional material for the sensing material. Alternatively, liquid metal such as eutectic Gallium-Indium (EGaIn) has also been found to be advantageous for soft sensors due to their good electrical conductivity and the ability to deform without breaking [205, 206]. It is often used with a stretchable encapsulation with microchannels that form the conductive circuits. However, the fabrication of soft sensors with liquid metal can be quite tedious as it involves multiple steps (Figure 16) such as the making of a mold, pouring and spin coating of resin, curing of the resin, injection of liquid metal, and sealing of microchannels. Among the soft sensors that are fabricated using non-3D printing techniques, the conventional thin film deposition technique is found to be a more popular technique due to the high dimensional accuracy and good conductivity of the fabricated material.

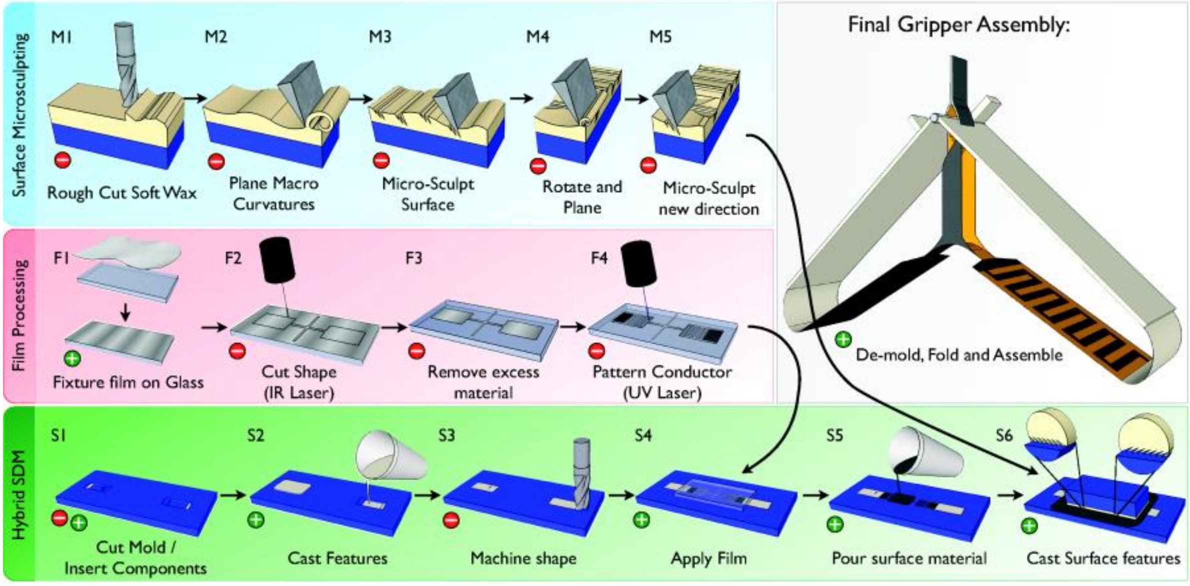


Figure 16 Non-3d printed sensor design involving multi-step fabrication Reproduced with permission, [207] Copyright 2015, American Society of Mechanical Engineers.

6.1 3D electronic printing techniques

Despite the many advantages that the thin film deposition techniques have brought, it is still limited in terms of material choice and design flexibility. In contrast, 3D electronic printing techniques offer advantages such as high-resolution thin film fabrication, compatibility with various substrate materials, a wide range of functional ink options, multi-material printing capability, and high design freedom [208-210]. So far, there have been numerous 3D electronic printing techniques that have been used for the fabrication of soft sensors and they can generally be classified into material-extrusion technique, material-jetting technique, and vat-polymerization technique. Even though they are considered as 3D printing techniques, these techniques use different printing mechanisms and therefore each of these techniques offers unique advantages compared to the others. As such, the following sections will provide a brief description of the working principle of the 3D printing techniques and discuss their respective advantages and disadvantages for the fabrication of soft sensors.

6.1.1 Material-extrusion techniques

Material-extrusion techniques belong to a class of techniques where the material is pushed through a nozzle and the extruded filament of the material is then deposited and patterned layer-by-layer. There are two main types of material extrusion techniques, namely fused filament fabrication (FFF) and direct ink writing (DIW) techniques. The two techniques differ in terms of the form of feedstock materials and the mechanism to form a bond with the underlying layers.

For the FFF technique, the feedstock materials are usually thermoplastics in filament form, therefore, a heated nozzle is required to melt the filament before it can be extruded for printing. For electronic printing, thermoplastics with conductive fillers are normally used to form the conductive filament for the fabrication of electronic components and devices [211]. Various types of conductive fillers have been explored such as silver particles, copper particles, carbon nanotubes (CNT), just to name a few [211, 212]. Besides, there have been several works that have demonstrated the fabrication of soft pressure sensors with CNT nanocomposite filament using the FFF technique [213]. Zapciu et al. have successfully demonstrated the fabrication of soft end effector embedded with conductive sensing elements that can do capacitive touch sensing and resistive bending sensing completely via the FFF technique [214]. One major advantage of using a multi-nozzle FFF technique is that the conductive thermoplastic filament can usually bond well with the underlying thermoplastic, thereby minimizing the impact on the structural integrity due to mismatch of material type. However, the issue with nanocomposite filaments is that they tend to have poor electrical properties due to the low particle loading of the conductive filler to ensure filament extrudability. Generally, various piezoresistive sensor designs have been successfully fabricated and demonstrated using the FFF technique [215-217].

DIW technique is very similar to the FFF technique, however, it does not require a heated nozzle as the feedstock materials usually are in the form of low viscosity liquid or paste. The ink is normally placed in a syringe barrel and extrusion of ink is normally done by moving a piston that is driven by a screw or pressurized gas. Various types of functional inks have been used for direct ink writing of soft sensors, which include nanoparticle ink [218], nanocomposite ink[219], and liquid metal ink [206]. For nanoparticle inks, it usually requires a binding agent and an encapsulation layer to improve the mechanical integrity of the printed conductive film [220]. In contrast, the nanocomposite ink is usually made up of stretchable material as the matrix such as PDMS resin or UV curable resin and loaded with a conductive filler such as metal particles or carbon nanotubes [221]. In such a case, the extruded filament must be cured by using heat or UV light as soon as it is deposited on the substrate to retain its shape. Despite not having the advantage of high electrical conductivity due to the presence of the matrix material, direct ink writing of nanocomposite ink allows for the formation of 3-dimensional electronic architectures that could be beneficial for unique applications such as a soft sensor. For instance, Xu et al. have developed a DIW-based co-extrusion technique for the fabrication of soft conductive structure with carbon as the core and PDMS as the shell for the extruded filament. They have made use of the DIW technique to fabricate a unique 3D cellular-based embedded resistive sensor that can be used for pressure sensing of a smart gripper [222]. On the other hand, instead of printing the conductive material, Yang et al. have demonstrated using DIW to print a scaffold-like dielectric layer made up of PDMS for a soft and stretchable capacitive sensor [223].

6.1.2 Material-jetting techniques

For material-jetting techniques, the functional inks are deposited and patterned through a nozzle or an array of nozzles. Generally, there are two main types of material-jetting techniques, namely inkjet printing and aerosol jet printing. In both cases, functional inks in liquid form are used as the feedstock material and can be considered as a droplet-based 3D printing technique. They differ in terms of the droplet-jetting techniques.

Inkjet printing is a process where ink is ejected through a nozzle to form tiny droplets that can be deposited on a substrate. The ink is forced out by the volume reduction of the chamber, usually through piezoelectric action or thermal action. Due to the small size of the nozzles, the deposition head of an inkjet printer normally comes with a compactly packed nozzle array that can speed up the fabrication process and support multi-material printing. One advantage of an inkjet printer is that different materials such as polymeric resins and conductive inks can be printed together in one build, to achieve high-performance embedded electronics and sensing circuits. Unlike 3D inkjet printing that uses photocurable resins, solvent-based conductive inks that are made up of conductive nanomaterials such as silver nanoparticles are normally used [224]. As the solvent starts to evaporate after being deposited, there will be a significant loss in the volume of the ink, resulting in the formation of the thin conductive film. The deposition pattern of the nanomaterial requires careful optimization of the ink rheology, surface energy of the substrate, the surface charge of the nanoparticles and the substrate, and the printing parameters. Generally, a homogeneous film is preferred for good and consistent electrical performance. Inkjet printing offers advantages such as high-resolution printing and multi-material printing, making it suitable for the fabrication of sensors that requires multiple materials such as capacitive sensors with parallel-plate design. For instance, Mikkonen et al. have demonstrated using inkjet printing to fabricate soft capacitive pressure sensors for tactile sensing using PDMS as the dielectric layer and silver nanoparticle ink for the conductive electrodes [225]. On the other hand, Faller et al. fabricated an integrated capacitive multimodal sensor using hybrid 3D printing technology that combines 3D printing and inkjet printing for the fabrication of a robotic gripper [226]. Interestingly, inkjet printing has been used for the coating of the passivation layer for smoothening of the surface of 3D printed structure to facilitate subsequent printing of electronics on the surface [227].

Aerosol jet printing (AJP), on the other hand, is a deposition process that controls the flow of the droplets pneumatically. The AJP process comprises 4 stages, namely ink atomization, aerosol transportation, aerosol focusing, and aerosol deposition [228, 229]. AJP process allows for a wide range of material as it can process inks with a wider viscosity range (1-1000 cP) in comparison to 10 cP of the IJP process. The high exit velocity of the ink from the nozzle allows for a high standoff distance between the nozzle and the substrate which is advantageous for printing on a surface with irregularities. Together with the 5-axis motion controller, the AJP process has been shown useful for integrating electronics such as sensors onto the surface of existing structures [230]. This can be useful for applications such as structural health monitoring [230]. Unlike the IJP process where the substrate material can be printed together with the electronics, it is often required to prepare the substrate for the electronic fabrication using AJP [231]. Also, various stretchable inks are compatible with the AJP process for the fabrication of stretchable and soft electronics [232-234]. Despite being less popular than the IJP process for the fabrication of soft sensors, there have been several works on AJP printed soft sensors [235, 236].

6.1.3 Vat polymerization techniques

Vat polymerization is a 3D printing technique that creates 3D objects using an energy source such as a UV laser to photo-polymerize a thin layer of uncured resin in the vat in a layer-by-layer manner. Due to the limitation of the printing technology, most vat polymerization 3D printers are only capable of printing a single material. Therefore, most of the time vat polymerization 3D printing technique is used for the fabrication of the sensor structure of the sensing element instead of the sensing electrode [237]. As the sensor structure must conduct electricity for sensing purposes, it is normally achieved by either using a nanocomposite resin with conductive fillers or by coating the surface of the sensor structure with the conductive film [237, 238]. Interestingly, Yin et al. presented the optical maskless stereolithography (OMsL) technology that can print 3D patterns made of soft hydrogel material (poly(acrylic acid) (PAA)) for miniature pH sensing, which has reference value for VP printing sensors with 3D structure [239].

6.2 Potential of 3D printed soft sensors for smart grippers

For conventional grippers, the fabrication and integration of sensors into the gripper structure are often done with a series of manufacturing processes. Often, grippers can come in different shapes and sizes to cater to different applications, making the integration of sensors a challenging and tedious task as the placement of the sensors needs to be considered on a case-by-case basis. With multi-material 3D printing, the sensors can be redesigned and integrated into the gripper's structure easily and quickly at a much lower cost. For instance, Kaur et al. have developed a soft gripper based on compliant cellular structures and integrated capacitive sensors for pressure sensing as shown in Figure 17 [240]. Both the structure and the sensor of the smart gripper are entirely fabricated using the FFF technique using flexible and conductive filaments respectively. With the pressure sensor, the smart gripper can detect the gripping force that is applied to the objects when using objects of different shapes and sizes.

Not only can the electronics be printed on the surface of the structure of the soft grippers, but they can also be embedded into the soft gripper structures with a suitable 3D printing technique. This allows the embedding of sensing arrays under the surface of soft grippers that mimic the human sensory system. This also provides additional advantages such as protection of the electronic components and a more compact sensing array design. For instance, Truby et al. developed an embedded 3D printing technique that is suitable for the fabrication of electronics with multi-layer and multi-material architecture (Figure 18A, B, C) [241]. They have successfully printed a soft gripper that is equipped with a contact sensor, an inflation sensor, and a curvature sensor that is capable of detecting various gripper's motions, types of objects, and gripping force. However, fabricating soft grippers with embedded sensors is still challenging because there are not many commercial printers that have multi-material printing capability. It normally requires the printer to have multiple print heads and ink reservoirs like the Polyjet® 3D printer in order to fabricate grippers with embedded sensing elements as demonstrated by Christianson et al. (Figure 18D) [242].

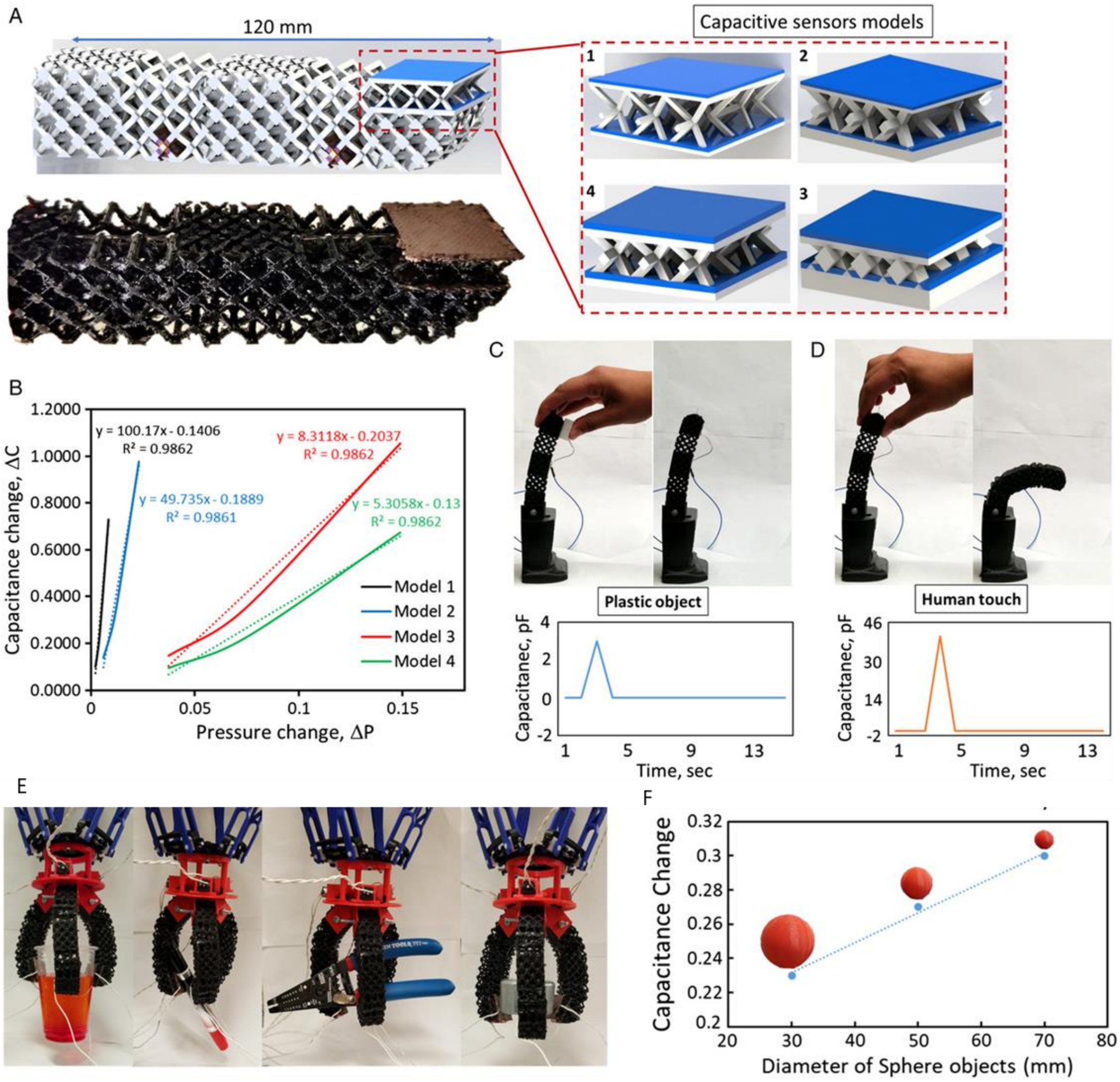


Figure 17 Images showing the compliant soft gripper structure with integrated capacitive pressure sensor fabricated using FFF technique. A) Various capacitive sensors at the tip of the gripper for tactile sensing B) Variation in capacitance of various capacitive sensors with pressure change C) Capacitance change when in contact with object D) capacitance change when in contact with human finger e) Gripper holding various objects F) Capacitance sensitivity concerning the diameter of sphere objects. Adapted under the terms of the CC-BY Creative Commons Attribution 4.0 International License. [242] Copyright 2019, Frontiers Media S.A.

Often, printing the electronics directly onto the structures can be expensive as it requires advanced 3D printing equipment. Fortunately, 3D printing also allows for low-cost sensor fabrication solutions thanks to the flexibility to utilize various kinds of flexible substrates for the fabrication of flexible sensors which can then be incorporated with the soft gripper structures. For example, Yang et al. made use of cheap substrates such as paper and a normal commercial inkjet printer to realize the low-cost fabrication of flexible sensors (Figure 19) [243]. The paper-based sensor containing a resistive strain sensor and a capacitive proximity sensor that is made up of recycled material can then be incorporated into the soft gripper for motion and proximity sensing. It was found that the sensor can reliably detect the bending angle of the actuator up to at least 30 times. The resistive strain sensor could gauge the size of items that it grabbed. As for the capacitive proximity sensor in the soft gripper, the sensor geometry was experimentally determined to be an interdigitated shape with a pitch of 300 μm and a width of 500 μm for the best sensitivity. The proximity sensor can measure the object's proximity at a high actuation rate of 25.307 (m^{-1} s^{-1}).

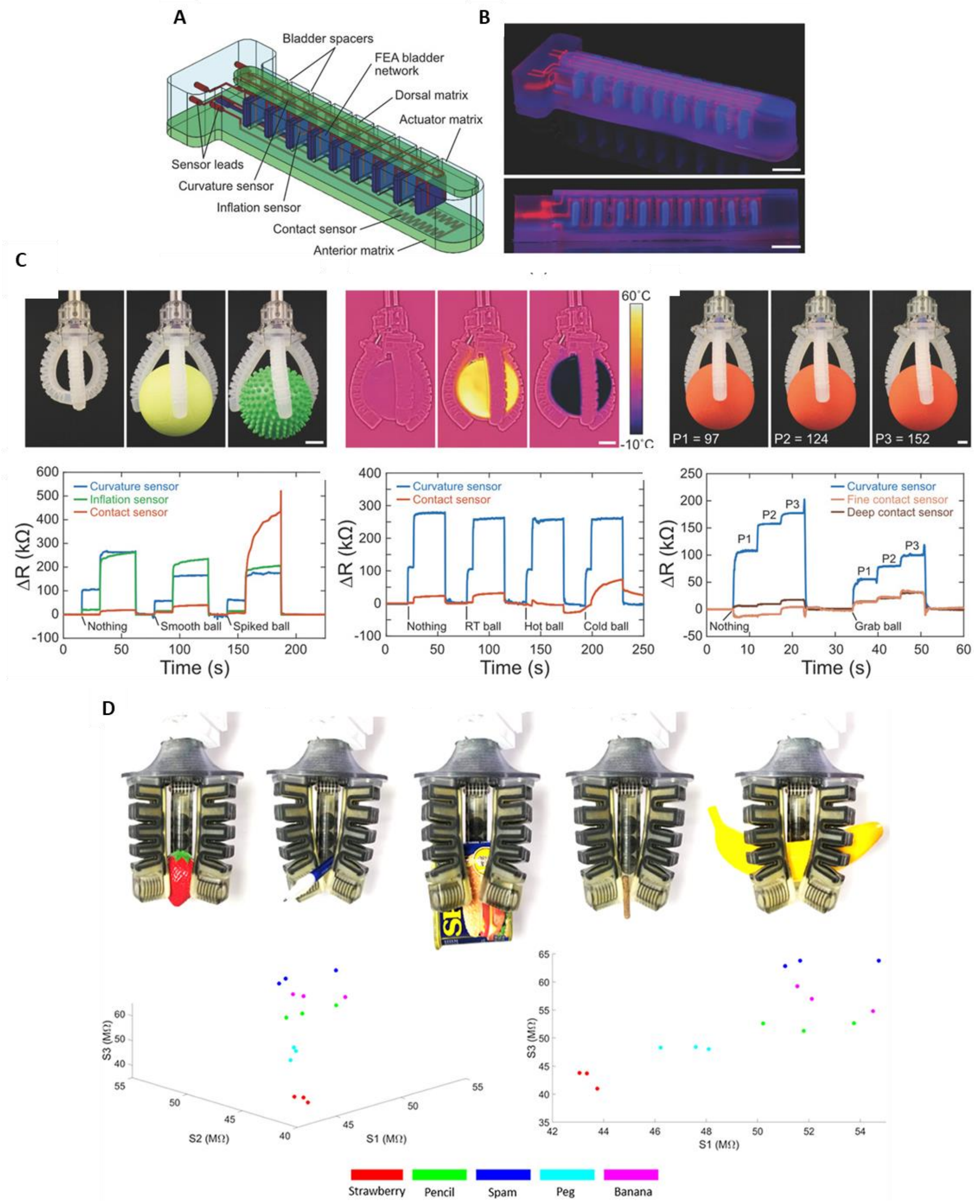


Figure 18 Soft sensors on grippers. A) Schematics of soft somatosensitive actuator [241]. B) Fabricated soft actuator fluoresces in blue (gripper structure) and red (sensor) to facilitate visualization. C) Gripper in action and resistance change during the actuation. D) Pneumatic gripper with embedded strain sensors and the sensors reading while holding various objects. Adapted under the terms of the CC-BY Creative Commons Attribution 4.0 International License. [242] Copyright 2019, Frontiers Media S.A.

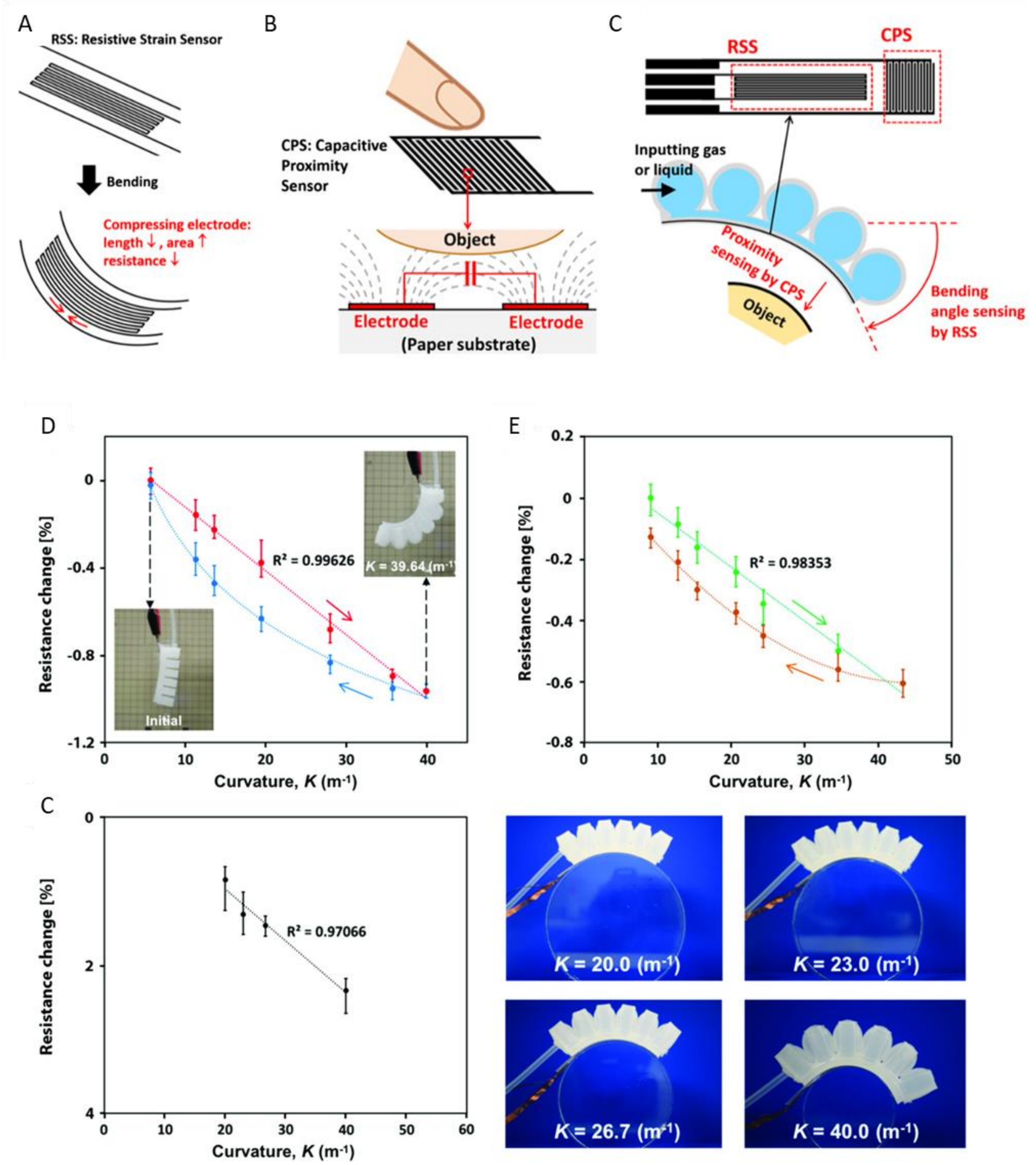


Figure 19 Sensor-Rich Fluidic Elastomer Actuators Embedded with Paper Electronics. A) working principle of resistive strain sensor B) working principle of Capacitive proximity sensors C) working principle of fluidic elastomer actuator D) Resistance change of the resistive strain sensor in the actuator E) Resistance change in pure bending (without the actuator) C) Resistance change at various curvatures of an object. Adapted under the terms of the CC-BY Creative Commons Attribution 4.0 International License. [243] Copyright 2020, Frontiers Media S.A.

Multidirectional tactile sensing has often been a challenge in the field of soft robotics. This is because conventional strain sensor only allows for uni-directional strain sensing which means that there is no facile method to realize multidirectional tactile sensing. With 3D printing, the sensing element can be designed to tailor for specific applications. Also, the high material processibility of 3D printing techniques allows for the use of material with high strain sensitivity to improve the performance of the sensor. For instance, Mousavi et al. used a self-developed highly strain-sensitive conductive filament with carbon nanotube fillers and used the FFF technique for the fabrication of a multidirectional tactile sensor that can accurately distinguish the direction of force (Figure 20) [212]. Also, the fabricated sensor has a reported gauge factor as high as 1342, making it sensitive enough to output a signal even with a very slight strain due to the gripper's motion.

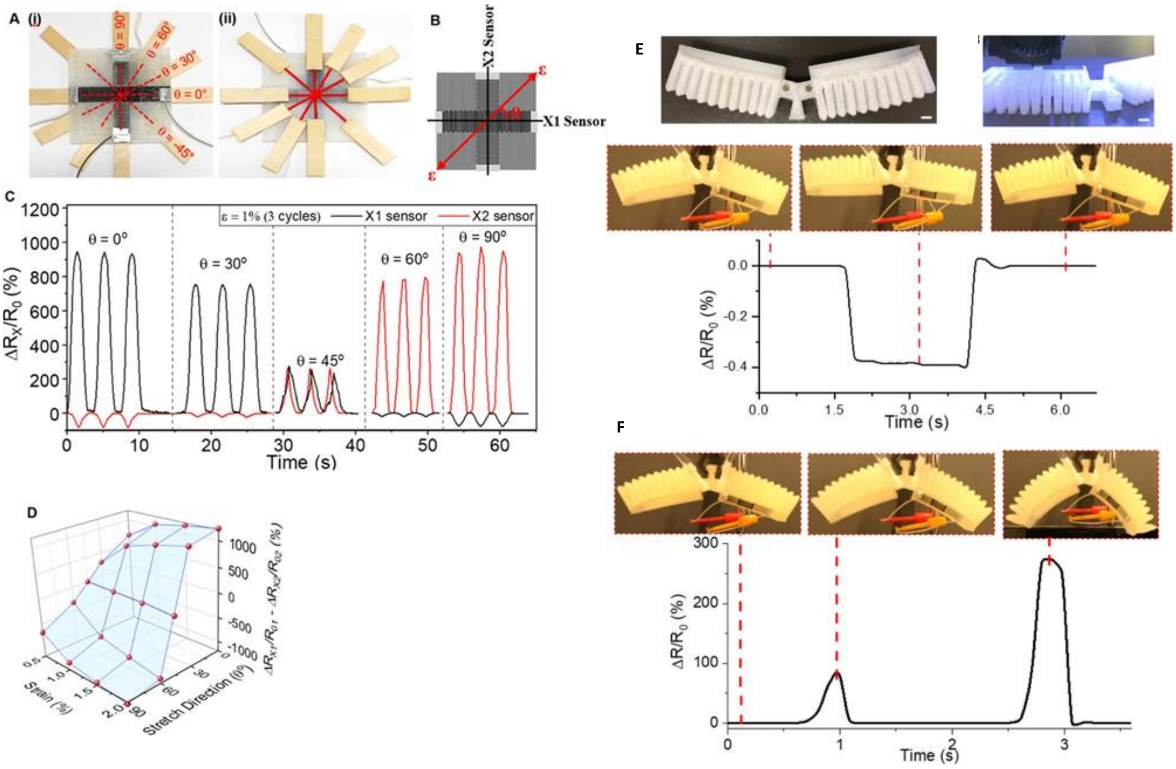


Figure 20 Electromechanical performance of the cross-sensor. (A-i) Front and (A-ii) back images of the 3D-printed cross-sensor showing the wooden strips used in tensile tests in different directions. (B) Illustration of a cross-sensor with 2 X-sensors (C) Tensile strain sensitivity test results in various directions. (D) Variation in resistance changes between X1 and X2 sensors plotted versus the applied tensile strain and angle ϑ. (E) Demo of the sensor response in the deflation/vacuum state (bending upward) and (F) inflated states (bending downward). Adapted with permission, [212] Copyright © 2020 American Chemical Society.

Besides, several works have used 3D printing indirectly for the fabrication of sensors. Various works have shown that highly sensitive soft sensors can be achieved with unique and periodic microstructures. However, the fabrication of such microstructures is often restricted by the poor printing resolution of the existing 3D printing techniques when using soft materials [244]. In such cases, a rigid mold with the negative image of the microstructure can be fabricated using the 3D printing technique first for the subsequent molding of the stretchable material as demonstrated by Chen et al. (Figure 21A, B, C, D) [245]. In addition, 3D printing techniques can also be used for the fabrication of the encapsulation or the microchannels for the liquid metal-based sensor for soft robotic applications [246-248]. For instance, Goh et al.

demonstrated the creation of soft microchannels structure using Projet® 3D printer and the injection of conductive ink into the microchannel to form the soft sensing element (Figure 21E, F, G, H, I) [248]. Despite not printing the sensing element directly, this method shows the potential of 3D printing for the fabrication of highly bendable and embedded sensors for soft robotics.

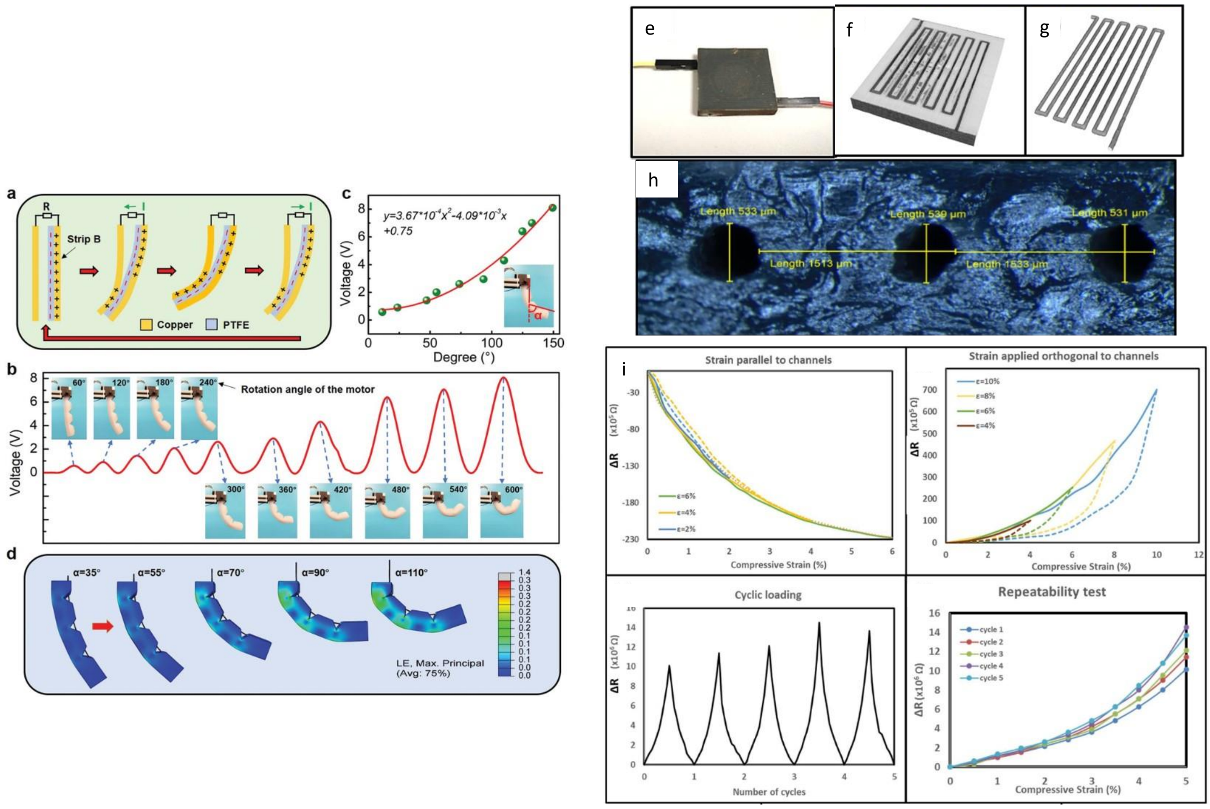


Figure 21 Indirect fabricated sensors in the soft actuator. A) diagram of the working principle of the inner TENG: the actuator curls inside to make the inner Strip-B (attached to the finger's chamber) contact with Strip-A (fixed on the holder) and the contact area increases with the bending degree of the actuator. B) Output voltages measured from the inner TENG at various bending degrees of the soft gripper. C) graph of voltage-bending angle fitted with a parametric equation D) FEA results showing deformation of the cable-driven soft gripper with respect to various curling degrees. A-D) Reproduced with permission, [245] Copyright © 2020 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim .E) 3D printed microfluidic sensor F) CT-scan image showing internal channels for conductive fluid. G) internal channels for the strain sensors H) cross-section of the sensor showing the internal channel I) performance of the 3D printed microfluidic sensor. E-I) Adapted with permission, [248] Copyright © 2016 Research Publishing, Singapore.

7. Challenges

7.1 Material availability for 3D printing

Although a wide range of materials have been developed for 3D printing, the material choice is still very limited, especially for soft materials. The material choice is normally tied to specific 3D printing techniques. For instance, the single-nozzle FFF and SLS can only process one material at a time, although blends of thermoplastics and thermoplastic composites have also been developed as the feedstock materials for these 3D printing techniques. These blends or composites normally have fixed compositions that cannot be varied during the printing process. On the other hand, the material jetting 3D printing technique allows the in-situ mixing of constituent material resins to form a wide range of material compositions.

The ability of the 3D printing techniques to fabricate multi-material parts enables the creation of novel gripper structure designs. The multi-material printing expanded the material library by having different combinations of constituent materials. However, the boundary properties between the two materials require further research to have a proper understanding of the performance and the reliability of the multi-material parts, especially for the grippers that perform the same action repeatedly for a few thousand times a day. Since the grippers have to go through repeated cycles, the material should have high toughness and resilience, and be able to work within its elastic range. Apart from having a high elongation at break, the material should also have high damage resistance and fatigue resistance. Yet, there are currently small numbers of soft materials that can be printed, and even fewer can meet these requirements. The service life of the elastic soft actuator relies greatly on the materials' fatigue performance. However, multiple investigations have shown that AM elastomers generally exhibit poor fatigue properties. Jacob and Christopher studied the fatigue performance of material jetting printed elastomers and discovered that at a test frequency of 1.7 Hz, the elastomer achieved a fatigue life of 106 cycles at a low elongation of 20% or less [249]. Nevertheless, elastomers exhibit very poor fatigue properties at higher elongation (102-103 cycles at 40-60% elongation) and have a maximum elongation to failure of about 70%. Research by Dammer et al. shows that the soft bellows actuator printed by PolyJet has poor fatigue performance [250]. If the connection between the pressure layers in the thin-walled bellows actuator is weak, this effect will increase. Bryan et al. performed a fatigue test on the DLP-printed SpotE elastomer, and the results showed that the elastomer failed after 9 ± 3 cycles under a 125% load [251].

Additive manufacturing causes anisotropy in the fabricated parts. The fast cooling nature of the AM manufacturing method will result in a thermal gradient in the printed part during the printing process, causing poor bonding between each layer. Due to the inadequate deposition of soft materials, voids can also be formed, resulting in higher porosity and decreased structural integrity of the manufactured parts. This effect will also increase when printing on soft materials with relatively low mechanical strength.

Numerous AM materials, particularly UV-curable materials, may degrade under prolonged exposure to UV. Although the Shore hardness of the SLA material does not change greatly after UV radiation and moisture aging, Young's modulus of the SLA material substantially increased, which indicates that the material is hardened [252]. Additionally, the shape and color of the printed parts would change due to moisture and ultraviolet aging.

7.2 Scalability

Most of the AM techniques have tiny print volumes and a slow print speed. While AM techniques can manufacture parts with multiple components incorporated into one single part, the limited print dimensions of the 3D printer may require the designer to generate the modular gripper designs rather than fabricating the whole grippers at once. The scaling up of the production is also challenging due to the post-processing issues such as curing and support material removal as well as the compromise between speed and resolution.

7.3 The removal of support material

Printing with soft materials is especially difficult without using support materials because soft materials would collapse under their own weight during the printing process, as the previously deposited layers cannot bear the weight of subsequent layers. Printing supporting structures or materials not only increases fabrication difficulty, time, and cost but also increases the risk of damage to delicate AM parts when the support structures are removed [253]. Pneumatically actuated grippers are normally designed to have hollow and thin-walled tubular features. This makes it difficult to remove support materials and structures for FFF-printed hollow structures, as the supports are often removed manually. To overcome the problem, several studies have used the bridging technique for FFF printing to print the top overhanging portion of the hollow structures without the use of supporting structures [69]. Gripper structures were also carefully designed to avoid overhanging structures to eliminate the use of support materials within the hollow cavity of the grippers. Another method for printing hollow channels or overhanging features with flexible materials is by using sacrificial support materials that can be chemically dissolved or removed [135]. The support material can be dissolved by melting or immersing in a solvent bath. In the powder bed fusion technique, the support removal is not much of an issue as the powder trapped in the printed gripper structures can be removed from the hollow pneumatic actuator inlet hole.

7.4 Design and control of soft gripper

In addition, to achieve the final implementation, one of the main challenges that the 3D printed soft gripper must still overcome is the design of the control system, which takes into account the shape of the objects being handled. To realize compliant gripping, grippers can be designed with multiple linkages with independent actuation in order to have complete control over the shape-changing of the grippers. However, this adds to the complexity of the gripper design and the difficulty in the fabrication. Simplified actuation of the under-actuated grippers has been developed to reduce the design and actuation complexity at the expense of the gripper's control freedom. Additionally, 3D printing also enables the tailor-made sensors to be directly fabricated onto the gripper structures. The customizable 3D printed sensors would require special calibration techniques that are specific to different gripper designs. Proper characterization of the 3D printed sensor would be needed to fully understand the performance and behavior of the 3D printed sensors so that the electrical signal measured can reflect the actual status and condition the grippers are in.

8. Future outlooks and conclusion

In this article, the use of 3D printing in the fabrication of robotic grippers and sensors for grippers are reviewed. Various gripper designs and the role of 3D printing in the creation of these grippers have been discussed. The benefits and limitations of various 3D printing techniques for the fabrication of grippers were evaluated.

The ability of 3D printing techniques to fabricate multi-material parts has opened up the possibility to fabricate functional soft grippers made of materials with different physical, mechanical, electrical, magnetic, and optical properties. Another manufacturing strategy is to make use of multiple additive manufacturing technologies to directly manufacture all the key components of the soft gripper in one process, including actuators, sensors, control, and power systems. The development of conductive materials for 3D printing has also enabled the creation of multifunctional structures, such as the grippers with sensing capability. It is normally achieved through the direct deposition of conductive inks on the gripper structures to form the sensing element, or the fabrication of gripper structures with polymers with enhanced electrical properties so that the whole structures can be used to sense.

Although this field is still new, it has seen a massive amount of research being carried out. The adoption of 3D printing technologies in the fabrication of grippers will only increase in the future because of their ability to fabricate customized grippers that are tailored for specific applications at a relatively low cost. Overcoming the challenges and issues in the material development and fabrication processes is key to advancing the creation of novel soft grippers. With the advancement of printable functional materials, 3D printing will make it easier to directly produce end-user soft grippers with complex designs and functions, using smart materials and direct fabrication of sensors.

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