A review of 3D printing processes and materials for soft robotics

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Abstract

Purpose- Soft robotics is currently a rapidly growing new field of robotics whereby the robots are fundamentally soft and elastically deformable. Fabrication of soft robots is currently challenging and highly time- and labor-intensive. Recent advancements in 3D printing of soft materials and multi-materials have become the key to enable direct manufacturing of soft robots with sophisticated designs and functions. Hence, this paper reviews the current 3D printing processes and materials for soft robotics applications, as well as the potentials of 3D printing technologies on 3D printed soft robotics.

Design/methodology/approach- The paper reviews the polymer 3D printing techniques and materials that have been used for the development of soft robotics. Current challenges to adopting 3D printing for soft robotics are also discussed. Next, the potentials of 3D printing technologies and the future outlooks of 3D printed soft robotics are presented.

Findings- This paper reviews five different 3D printing techniques and the commonly used materials. The advantages and disadvantages of each technique for the soft robotic application are evaluated. The typical designs and geometries used by each technique are also summarized. There is an increasing trend of printing shape memory polymers as well as multiple materials simultaneously using direct ink writing and material jetting techniques to produce robotics with varying stiffness values that range from intrinsically soft and highly compliant to rigid polymers. Although the recent work done is still limited to experimentation and prototyping of 3D printed soft robotics, additive manufacturing could ultimately be used for the end-use and production of soft robotics.

Originality/value- The paper provides the current trend of how 3D printing techniques and materials are used particularly in the soft robotics application. The potentials of 3D printing technology on the soft robotic applications as well as the future outlooks of 3D printed soft robotics are also presented.

Keywords Additive manufacturing; 3D printing; Multi-materials; Soft materials; Soft robotics

Paper type General review

1. Introduction

Additive manufacturing (AM), or more commonly known as 3D printing, is a group of techniques that join materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing techniques such as machining. With the advances of technology, 3D printing has been increasingly adopted for the creation of the end-use parts (Goh et al., 2017, Yap and Yeong, 2014, Carbon, 2017). The manufacturing of end-use parts using AM could take advantage of the increased design freedom offered by AM to enhance the part functionality. Nonetheless, not all the materials are readily printable, limiting the extent of adoption in the structural applications as many AM materials are not strong or durable enough. Hence, current research focus in AM community has been steered towards new material development and process development to enable printing of common engineering materials such as composites (Goh et al., 2018), ceramics (Sing et al., 2017) and elastomer (Ge et al., 2013).

The advancements in 3D printing of soft materials have enabled greater design complexity and faster fabrication of soft robots. With inspiration from nature, soft robotics is currently a rapidly growing new field of robotics whereby the robots are fundamentally soft and elastically deformable and adapt their shape to external constraints and obstacles (Kim et al., 2013). Conventional robotic systems are mostly made of rigid mechanical components such as links and joints so that they can perform extremely fast, precise, powerful and repetitive position control tasks efficiently. However, the robotic systems have to be less rigid and more flexible to have the capabilities to perform more adaptive and flexible interactions with complex unpredictable environments, and to become more lifelike and compatible for human interaction (Iida and Laschi, 2011, Lipson, 2014). Some examples of applications include automated agricultural robots for fruit harvesting (Chua et al., 2003, Chowdhary et al., 2019), medical devices for surgery (Phee et al., 2008, Diodato et al., 2018), wearable soft robots for rehabilitation (In et al., 2015, Maeder-York et al., 2014, Polygerinos et al., 2015) and robotic bin picking (Anandan, 2016, Homberg et al., 2015).

Soft robotics not only require the use of flexible and soft materials like elastomer and toughened polymers to lend themselves to highly flexible and deformable structures, but it also needs another material to act as a stiffener to achieve manipulation and locomotion capabilities and/or directional control (Calisti et al., 2011). This can be achieved by insertion of another strain limiting material with higher rigidity into the soft-bodied system. Many of the existing soft robotics are inspired by the biomechanical features of soft-bodied animals and are made of intrinsically soft, extensible and highly compliant materials that can deform and absorb energy during a collision (Rus and Tolley, 2015). Soft components allow the animals to conform to various surfaces, and to lower the impact force or stress concentration by distributing the stress over a larger contact area. This is especially important for soft robotics interacting with soft materials such as tissues and organs and encountering deformable surfaces such as mud and soft soil as stress concentrations may cause physical injury with humans or robot immobility, respectively (Majidi, 2014).

Many conventional fabrications of soft robots involve molding and casting that can be customized, and 3D printed. Direct 3D printing of soft robots has yet to become one of the mainstream fabrication techniques due to material constraints. Nevertheless, as more materials are compatible with existing 3D printing technology, they are increasingly replacing the conventional soft robot fabrication approach of molding and casting.

There is a lot of ongoing efforts in the development of 3D printed soft robots at various scales. A few comprehensive articles are reviewing the 3D printing technologies and materials for soft robotics, and each of these reviews have presented several research potentials such as optimization of both material and printer for printing soft materials (Walker et al., 2019), integration of soft actuators and sensors through multi-material printing (Wallin et al., 2018) as well as biological *in vitro* and *in vivo* soft robots (Gul et al., 2018).

This paper aims to present the state-of-the-art review on 3D printing of soft robotics. Various existing 3D printing techniques and 3D printed materials, including elastomers, flexible materials, shape memory materials, and smart composites, that have been used for soft robotics are surveyed and presented. Limitations and advantages of each 3D printing techniques are highlighted. Also, the challenges of current 3D printing technologies that are relevant to soft robotics are presented. Next, the potentials of 3D printing technologies and 3D printed materials that could bring about value-adding and improvement to soft robotics are discussed. Finally, the paper highlights the challenges faced to adopt 3D printing for soft robots and the future directions of 3D printing of soft robotics.

The literature review for this review paper was carried out on the Web of Science database, with publications dated from 2005 to 2019. 592 combined search results were obtained from two sets of keywords "3D printing, additive manufacturing or rapid prototyping" and "soft robot, soft robotic or soft actuator". In this paper, 47 publications that fulfil the selection criteria of direct 3D printing of soft robotic components and 3D printing of soft materials for actuation purposes have been selected and discussed in Section 2.

2. 3D Printing Techniques and Materials for Soft Robotic Applications

There are generally five 3D printing techniques that are used for soft robotic applications, they are: material extrusion which includes fused deposition modeling (also known as fused filament fabrication) and direct ink writing, vat photopolymerization, powder bed fusion and material jetting. The process mechanism of each 3D printing technique and materials used to produce the soft robotics and the types of soft robots being fabricated using each technique are summarized in Table 1 and reviewed in the following sections.

Table 1 3D printing techniques used for fabricating soft robotics

3D printing techniques	3D printed materials	Typical design	Typical size	Actuation method	Advantages	Disadvantages
Fused Deposition Modeling or Fused Filament Fabrication	• Thermoplastic elastomer (TPE) filament • Filament made from shape memory polymer (SMP)	• Tubular gripper • Fingers-like grippers	Diameter: >10 mm Length: <150 mm	• Pneumatic	• Cheap • SMP can be formed into filament and be printed • High load to weight ratio	• Materials that are too soft or have too high transition temperature are challenging to be printed properly • Materials have generally higher hardness
Direct Ink Writing	• Elastomer • Silicone	• Tubes • Simple 3D constructs	Depends on the setup and material	• Pneumatic • Electric • Magnetic	• Functional materials or elastomers with particles can be printed • Multiple materials can be printed	• Extra curing after every layer might be needed and slows down the printing
Vat Polymerization	• Hydrogels (PEGDA) • Elastomer-like resins • Silicone	• Tubular grippers • Beam-like grippers	Length: <50 mm	• Pneumatic • Other activating layers such as residual stress from cell sheet • Light-actuated	• High resolution (0.2 mm thin wall can be printed) • Complex designs can be printed	• Materials tend to have a low ultimate strain • Poor fatigue properties
Powder Bed Fusion	• TPU92A-1 • PA12	• Multi-arm snake-like kinematic structure • Multi-fingered hand	Depends on the machine	• Pneumatic • Bowden wire	• High resolution • Complex structures can be printed • No support structures/materials needed	• PA12 is not an elastomer and would yield and deformed plastically
Material Jetting	• Elastomer-like resins • Acrylic-like resins • Epoxy and Polyurethane	• Bellows • Membranes • Octopus-like tentacle shapes	Height: >90µm Length: 200 mm	• Pneumatic • Shape memory wire	• Multi-material designs can be printed • Fast printing speed • High resolution	• Limited material selection • Poor fatigue properties • Costly • Material tends to have a low ultimate strain

2.1. Material Extrusion

2.1.1. Fused Deposition Modelling or Fused Filament Fabrication

Fused deposition modeling (FDM), also known as fused filament fabrication (FFF) is one of the most heavily adopted material extrusion 3D printing processes whereby the thermoplastic filament is melted by the liquefier and then extruded through a nozzle onto a platform. As the filament is deposited continuously on the print platform, it cools and solidifies while forming bonds with the surrounding materials, producing the 3D objects (Brian et al., 2014). FDM is highly compatible with a broad range of materials, including acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), nylon and polycarbonate (PC). Because of the relatively cheap and easily available and reliable desktop FDM printers, this technique has been heavily used to fabricate the molds for casting the commercial elastomer such as silicone (Onal and Rus, 2012).

Anver et al. (2017) printed the soft monolithic fingers and gripper using an FDM printable and commercially available thermoplastic elastomer (TPE) filament, FilaFlex (Recreus, Spain). The air chambers were specially designed with stronger lateral support to eliminate the use of supporting rafts during printing. Mutlu et al. (2016) also fabricated a soft robotic finger using FilaFlex and the printed soft robotic finger was assembled with a stiffness augmenting unit made of thin polyvinyl chloride (PVC) sheets. The stiffness of the robotic finger was controlled by the position and thickness of the stiffness augmenting unit within the channels of the soft robotic finger. Stiffness of the soft robotic finger could increase up to 40% by increasing the thickness of the stiffness augmentation unit. One advantage of this method is that it does not require an external pressure source to control the flexible components or a servo drive to control the overlapping layer and friction. Yap et al. (2016) also printed the bellow-type actuators directly with the FDM technique using the commercially available thermoplastic polyurethane (TPU) filament, NinjaFlex (NinjaTek, PA). Extensive experiments and finite element simulations were carried out to characterize and model the bending behavior and force soft pneumatic actuators under different pressures. In addition, cyclic testing was also performed to investigate the durability of 3D printed actuators. Soft grippers and a soft robotic hand exoskeleton were developed and have shown high customizability and high payload-to-weight ratio, as compared to other molded soft grippers. Keong and Hua (2018) also used the Ninjaflex for their 3D printed soft pneumatic actuator. The actuator, which has a fold-based design to achieve different bending profiles through variations of fold designs and placement of the strain limiting layer, can generate high force output at a safe pressure (Figure 1a). Igus (Igus, 2018) developed the FDM-printed flexible grippers made from the iglidur® filament for Carecos Kosmetick GmbH. The grippers with flexible elements are used to screw on lids onto jars for cosmetic products. The 3D printed grippers are also lighter and wear-resistant and they enabled up to 85% cost saving compared to previously aluminium grippers.

Elgeneidy et al. (2018) utilized the FDM printer with a dual-extruder print head which allows simultaneous printing of the flexible and conductive filaments, to directly print the flexible strain sensors onto a bending actuator. The actuator body was also printed using Ninjaflex while the sensing tracks were printed using conductive PLA filament from ProtoPasta. The flexible sensorized bending actuator can be calibrated to provide bending feedback and simple contact detection, as shown in Figure 1b.

Song et al. (2017) fabricated a soft actuator by combining FDM-printed scaffold structures with embedded wires to achieve bend-twist coupled motion. By controlling the raster angles of the different plies in the scaffold structures, symmetric and asymmetric bend-twist motions can be achieved upon pulling of the wire. James et al. (2015) made use of the FDM technique to fabricate soft active structures using the electroactive ionomeric polymer to create a 3D soft ionic polymer-metal composite (IPMC), namely the Nafion precursor filament. After the precursor polymer is printed, it undergoes a hydrolysis process and effective electroless plating process to induce electro activity in the 3D-printed models, to create a functional IPMC. Results from this study showed that the deflections achieved by the 3D printed IPMC was like that of those fabricated from commercially available Nafion sheet stock. However, the printed actuator shows a slower response and slower back relaxation effect than the conventional IPMC.

Yang et al. (2016) processed the shape memory polymer (SMP) (DiAPLEX MM-4520) pellets into FDM printable filament feedstock. A robotic gripper was fabricated, as shown in Figure 1c, to demonstrate the shape morphing capability of the SMP gripper when it is being heated above its glass transition temperature.

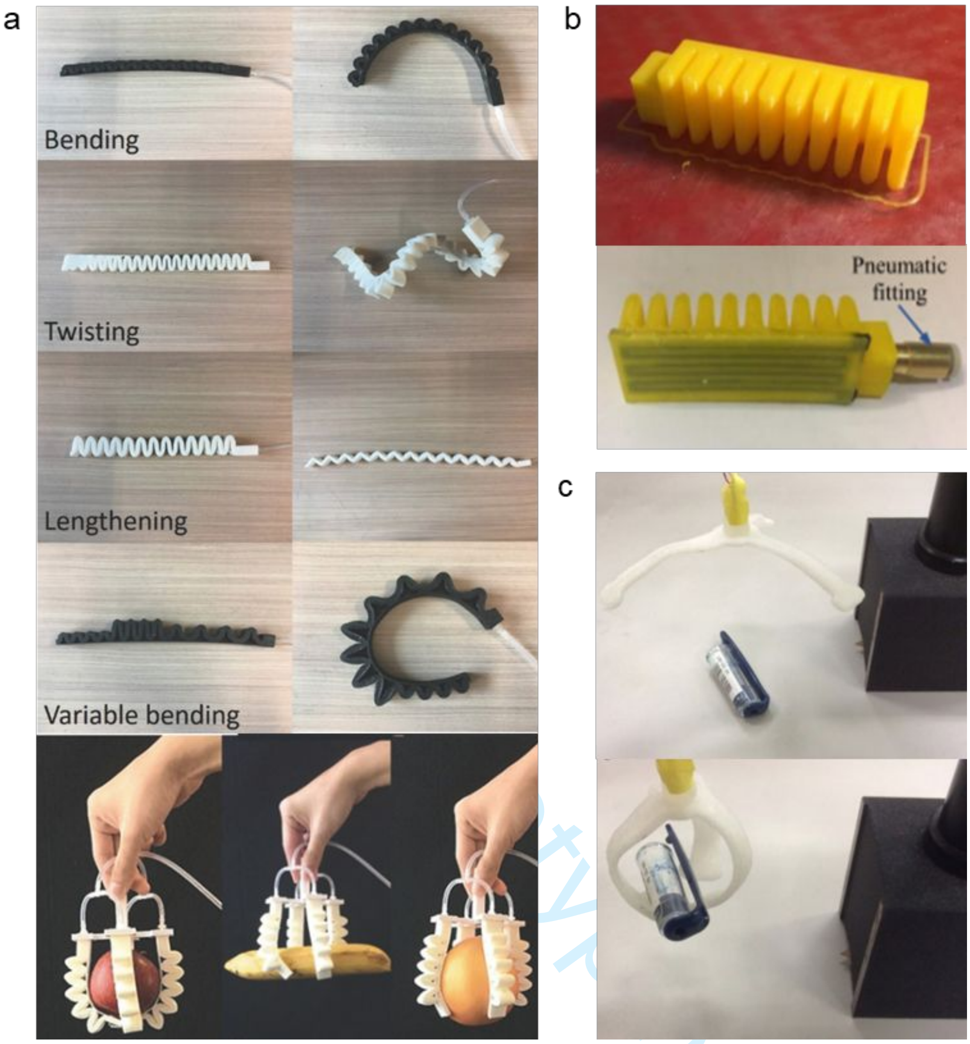

Figure 1 Examples of soft robots printed using the fused deposition modeling (FDM) technique. (a) Various bending profiles can be achieved through different fold designs and placement of the strain limiting layer, and a soft robotic gripper demonstrating its object manipulation capability (Keong and Hua, 2018), (b) Flexible sensors and soft actuators that are both printed simultaneously using the dual-extrusion print head FDM printer (Elgeneidy et al., 2018), (c) SMP gripper in the original state and activated under stimulus to grasp a pen cap (Yang et al., 2016).

2.1.2. Direct Ink Writing (DIW)

Direct ink writing (DIW) is a 3D printing process in which ink passes through a nozzle under ambient conditions in a controlled manner. Upon deposition, the ink solidifies into a solid object through different processing steps such as photopolymerization or thermal curing. DIW relies on the fluid-flow-based printing of a viscoelastic ink and the ink retains its shape after extrusion by its shear thinning behavior. To induce the flow through the nozzle in DIW, the deposition of the ink is controlled by a pressure source such as a plunger that applies a pressure larger than the yield stress of the ink. DIW technique can pattern printable inks that are formulated from a broad range of molecular, polymeric or particulate species. The ink can be selected based on its flow characteristics such as viscosity, surface tension, shear stress, and shear elastic and loss moduli (Truby and Lewis, 2016). Through careful control of ink composition, rheological behavior, and printing parameters, DIW can construct 3D structures that consist of continuous solids, high aspect ratio, or freestanding features (Lewis, 2006). DIW has shown various prospects in the domains of tissue engineering scaffolds (Fu et al., 2011), piezoelectric components (Li et al., 2015), microfluidic systems (Therriault et al., 2003) and photonic bandgap materials (Gratson et al., 2006).

Morrow et al. (2017) printed the soft robotic actuators by direct extrusion of pre-mixed silicone using a syringe needle and pump. Each printed layer of silicone was heat treated using a heat gun to accelerate the crosslinking of silicone before the next layer is printed. Despite having printing height error of 5% and large percentage error in the wall thickness due to the flow of the silicone during printing, the 3D printed soft actuators could respond closed to the molded actuator, with a small average error of ~5%.

Yirmibesoglu et al. (2018) have developed a DIW printer to fabricate two-part platinum cure silicones. The printed soft robotics have shown similar or better performance than the molded counterparts while being stronger and more reliable. It is also demonstrated that the fabrication time of 3D printing is only 1/4 of that of molding, and 3D printing of soft robotics requires less human intervention and a reduced number of fabrication steps. In another study, Schaffner et al. (2018) developed a multi-material DIW of light-curable silicones that enables locally tunable stiffness into pneumatic driven soft actuators with high freedom of programmable motion. After printing the cylindrical elastomeric body, stiff fibers were coated onto the polymerized silicone cylinder by continuously turning the cylindrical part while the nozzle deposits the stiff ink. Learning from the bio-inspired muscular hydrostats, the lead angle of the fiber winding and printing orientation of the stiff fibers were altered to achieve various programmed motions including elongation, contraction and twisting motions, as shown in Figure 2a.

Kim et al. (2018) adopted the DIW technique to print an elastomer composite containing ferromagnetic microparticles (Figure 2b). Magnetic field is applied to the dispensing nozzle while printing to impart patterned magnetic polarity to printed filaments. The magnetic ink consists of magnetizable neodymium-iron-boron (NdFeB) microparticles and fumed silica nanoparticles embedded in silicone rubber matrix containing silicone catalyst and crosslinker. By switching the applied field direction or changing the printing direction, the magnetic polarities of the printed inks can be controlled and tuned. The shape morphing structure can deform up to strain levels of 0.15 to 0.25 within 0.1 s to 0.5 s, demonstrating a much higher actuation rate than existing shape transforming soft materials. Another study by Roh et al. (2019) directly printed the polydimethylsiloxane (PDMS) homocomposite capillary pastes which contain 20 wt% magnetic particles using DIW. The elastin-like soft mesh can be actuated through the use of magnetic forces of a single electromagnet, mediated by capillarity, while floating on water, performing controlled shape change by laterally contraction and expansion of the mesh. The soft mesh demonstrated the potential as a soft extending grabber to capture an object floating on water, as well as magnetic responsive water droplet dispenser that could be useful in droplet microfluidics and drug release devices.

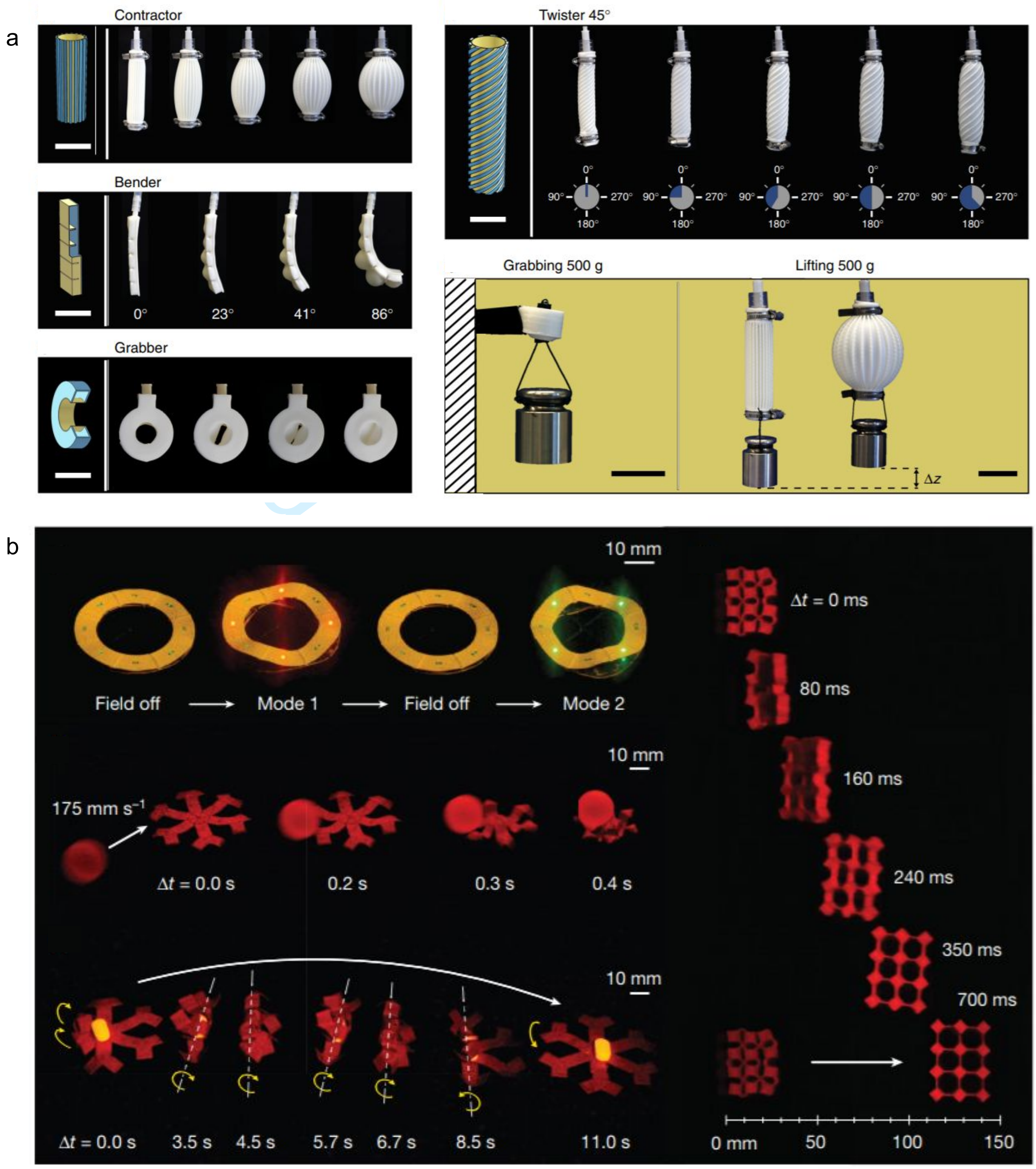

Figure 2 Examples of soft robots printed using direct ink writing technique: (a) contractor, bender, and twister fabricated using silicone with variable stiffnesses (Schaffner et al., 2018), (b) soft robotic systems encoded with intricate patterns of ferromagnetic domains depending on the magnetic polarities of the filaments in the 3D construct (Kim et al., 2018)

2.2. Vat Photopolymerization

One of the earliest and most established vat photopolymerization method is Stereolithography (SLA). SLA process builds an object by selectively scanning a vat of photopolymer resins using laser or other UV light sources. Each layer of the object is printed by moving a UV light beam on the surface of the resin by steering it in X and Y directions with galvanometric mirrors. After printing the first layer, the build platform lowers one layer and another fresh layer of resin is recoated by a blade to cover the already polymerized object. The photopolymers are sensitive to UV lights and would be crosslinked upon scanning. There are also other types of vat photopolymerization 3D printing techniques such as digital light processing (DLP), light crystal display (LCD), continuous liquid interface production (CLIP) and two-photon polymerization (2PP). DLP, LCD, and CLIP have faster printing speed since the entire cross-section of a layer is illuminated and solidified by the projection of a mask pattern, as compared to SLA that uses point-source laser radiation. LCD-based printing is a relatively new process that uses an affordable LCD screen that produces lesser distortion and higher resolution, as compared to DLP that uses the expensive digital micromirror device (Quan et al., 2020). However, since the LED light source in the LED-based printers has lower light intensity and power than that in DLP, it could not work with a wide range of resin.

On the other hand, 2PP, which is known for its highest printing resolution (~100 nm), is mainly used to 3D print micron-scale structures with complex architecture for applications such as micro-electromechanical systems, drug delivery devices, microfluidic devices, scaffolds, etc (Nguyen and Narayan, 2017). The design and fabrication of soft material, particularly hydrogels, has been a significant research area in 2PP microfabrication (Xing et al., 2015). Several studies have reported the stimuli-responsive hydrogels fabricated by 2PP exhibiting physical changes in response to ions (Xiong et al., 2011), temperature (Han et al., 2018b) and humidity (Lv et al., 2018). A recent study by Zheng et al. (2020) has also demonstrated successful fabrication of microactuator using 2PP where the light-driven 3D hydrogel actuator, with a size of ~26 µm, exhibits fast response and good reversibility. Another study by Soreni-Harari et al. (2019) presented an multi-step approach of 2PP multi-material fabrication using elastomer and rigid material to produce a 2 mm microrobots with flapping wing mechanism that can undergo large deformation.

Chan et al. (2012b) developed a biological soft robot that is actuated with residual stress of printed cantilever structure and the contractile forces of a cardiac cell sheet attached to the cantilever structure. The cantilever structure was printed with hydrogels using the stereolithography technique while the cells were seeded onto the structure to provide retraction force onto the structure. In another work, Chan et al. (2012) also presented the feasibility of printing two different hydrogels in the same 3D construct using SLA by switching resin vats. In a recent study by Goswami et al. (2019), commercial flexible photopolymer was used to 3D print the low-density, 3D architected soft machines (ASMs) using the stereolithography technique. It was shown that upon tendon-based actuation, the deformation and motions, such as contraction, twisting, bending and cyclic motions, are dependent on the topological structure including the types of lattice or tessellations, the thickness of the beam, and the cell size of the tessellations. However, this design method is currently limited by the resolution of 3D printing as well as the availability of 3D printable elastomeric material. Hence, the authors have also fabricated ASMs using silicone (Ecoflex 00-30) by injection molding from a 3D printed mold, and the ASMs could perform ultrahigh reversible compression (400%) and extension (500%).

DLP stereolithography technique was used to fabricate soft actuators using commercial photopolymers such as TangoPlus from Stratasys (Ge et al., 2018) as shown in Figure 3a, and Spot-E from Spot-A Material (Bryan et al., 2015) as shown in Figure 3b. Due to the high resolution of the DLP technique and material compliance, it was proven to be able to prototype soft actuators with relatively good deformation capability, despite the relatively low ultimate strain of the cured resin. To overcome the limited ultimate strains and low fatigue strength in the commercially available resin, Wallin et al. (2017) formulated silicones that are highly extensible with stiffness closed to natural tissues, and directly printed the antagonistic pair of fluidic elastomer actuators, as shown in Figure 3c, using the DLP technique to showcase its potential in achieving soft robotics with highly complex 3D architecture and long life cycle of (~50% of the maximum actuation amplitude over 5000 times). Besides, the material system permits self-healing via sunlight-induced photopolymerization to reseal the torn actuator within 30 s.

Smart composites that are electric field and magnetic field responsive have also been 3D printed via vat photopolymerization processes. Han et al. (2018a) printed soft actuators using the electroactive hydrogels (EAH) which is highly deformable in response to an electric field. DLP technique was used to photopolymerize the EAH precursor solution. EAH printed beam placed in phosphate-buffered saline electrolyte exhibits bending deformation when an electric field is applied due to the difference in osmotic pressure between the interfaces on the anode side. A gripper and an object transporter were printed with actuation elements, as shown in Figure 3d, and they have different characteristic thicknesses and hence the actuation speed to demonstrate the soft robotic manipulation. Bidirectional locomotion was also showcased using a 3D printed humanlike EAH structure through the deformation-induced shift of the center of gravity in an electric field. A recent study by Joyee and Pan (2019) has utilized the magnetic field-assisted projection stereolithography process to produce a magnetic field responsive soft robot with bi-axial locomotion capability. The locally programmed magnetic particle distributions in the anterior and posterior legs of the soft robot have attributed to an untethered magnetic actuation that allows crawling, steering and turning locomotion. The study also showcased the locomotion performance of the printed soft robot for drug delivery in a synthetic human stomach structure. With the magnetic actuation guide, the soft robot can crawl through the narrow esophagus and uneven structure while carrying liquid drugs without spilling.

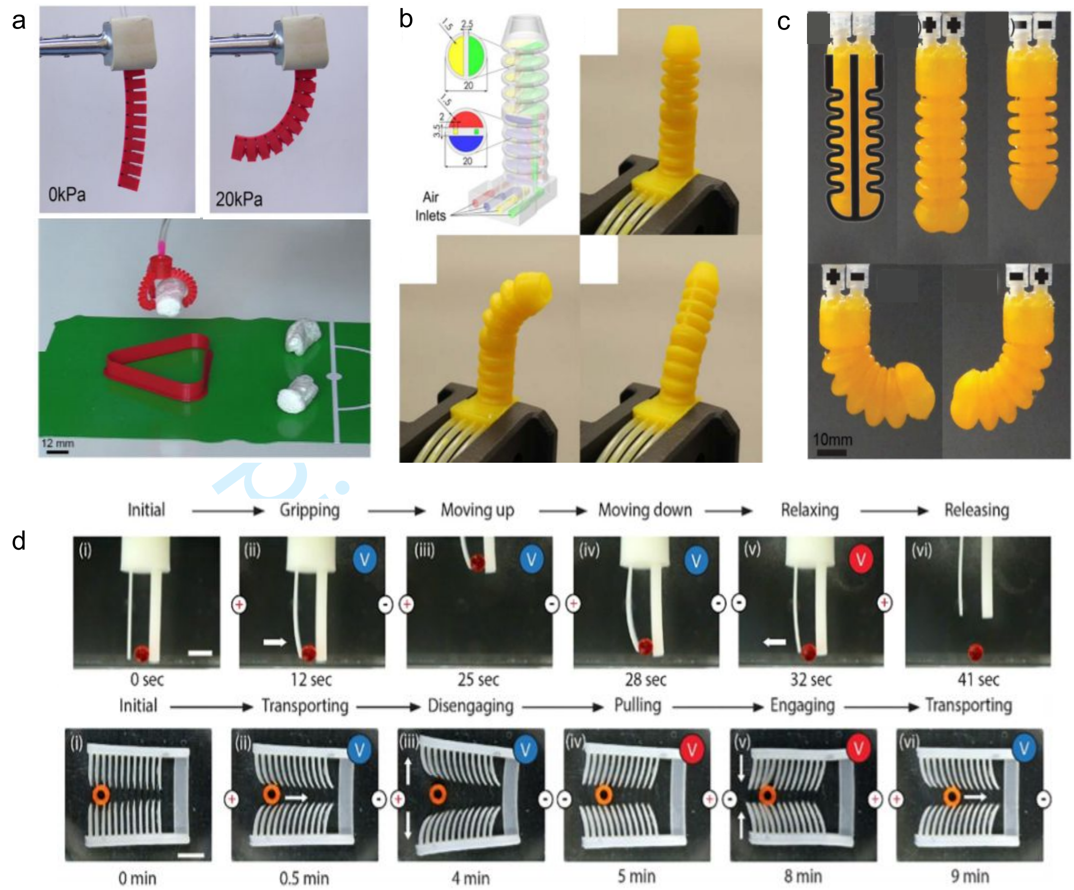

Figure 3 Examples of soft robots printed with Stereolithography. (a) flexible finger and gripper printed using TangoPlus from Stratasys (Ge et al., 2018), (b) flexible fingers printed using Spot-E (Bryan et al., 2015), (c) An antagonistic pair of silicone actuator that has the self-healing properties (Wallin et al., 2017), (d) gripper and transporter fabricated using electroactive hydrogels (EAH) can actuate under the application of electric field (Han et al., 2018a)

2.3. Powder Bed Fusion

Selective laser sintering (SLS) is a powder bed fusion process that builds objects from solid grains of powder. The polymer powder in a powder bed is locally heated to a temperature that is just below the powder's melting point then a rastering laser scans across the surface of a powder bed and selectively fuses the powdered material. Then the next layer of polymer powder is deposited and rolled across the print platform, and the laser sintering process is repeated until the desired 3D model is built completely. The unsintered powder can act as the support material and they can be reused after printing. Two of the common SLS materials are polyamide 12 (PA 12) and thermoplastic polyurethane (TPU), which are intrinsically stiff but can be flexible depending on the 3D geometrical design and wall thickness.

The FESTO Bionic Handling Assistant (BHA) consists of a resilient gripper arm whose structure and overall functional principle imitate an elephant's trunk and three fingers whose structure is based on the Fin Ray Effect (FESTO, 2012). Manufacturing using PA 12 by SLS, the thin-walled bellow structure is flexible and resilient to hold and transport sensitive objects with varying contours while the necessary stiffness is provided by the precise pneumatic control. The BHA has overall eleven degrees of freedom to perform a variety of task-specific travel paths that are not linear.

Rost and Schädle (2013) developed an SLS printed multi-fingered robotic hand using bellow actuators that is capable of performing tasks including gripping, lifting and rotating a sphere or a cube, via Reinforcement Learning. Scharff et al. (2017) used flexible polyurethane TPU92A-1 via the SLS technique to fabricate the bellow designed soft robotic hand. The robotic hand consists of 4 uniquely designed components: bending, rotational and bidirectional actuator, as well as the sensing air chambers.

Fischer et al. (2015) fabricated the CamBot which is an interactive soft actuator that can communicate and react to human actions. The robot is made up of 12 individual thin-walled air chambers printed using PA 12. On the other hand, Roppenecker et al. (2013) used the flexure hinges and compliant mechanisms that are printed with PA

12 powder using the SLS technique, to achieve snake-like kinematics that can manipulate flexible endoscopic instruments. SLS technique was also used to fabricate the anthropomimetic robot that replicates the human upper limb using PA 12 powder (Jäntsch et al., 2013). Besides having the ability to customize the tendon canals and ducts for the wiring, 3D printing has also reduced the part counts and produced a thin wall lightweight design in this complex robot.

2.4. Material Jetting

Material jetting is an additive manufacturing process in which the inkjet print heads jet the liquid resin onto the platform before solidifying. PolyJet printing process from Stratasys is one of the most established material jetting printing processes. Droplets of the photopolymer materials are selectively dispensed through the tiny nozzles in the print heads, which consist of numerous linearly aligned nozzles. They are immediately UV-cured and solidified to build the 3D structure after undergoing crosslinking in response to UV light, then the next layer repeats until the model is built completely. Commercial resins based on methacrylate or acrylate chemistries with distinct physical and mechanical properties can be simultaneously deposited selectively to fabricate 3D multi-material models directly. A single printed part can have a variety of mechanical properties, opacities, and colors (Vaezi et al., 2013). The major commercial material jetting 3D printers are the PolyJet from Stratasys and MultiJet from 3D Systems. Both companies have their proprietary materials including the rigid plastics and flexible urethane-acrylate. Multiple different materials can be fed into the print heads and can be jetted selectively together with the support materials. The functionally graded structure can also be fabricated through selective deposition of different materials in different ratios. For instance, digital materials with Shore A ranging from 35 to 100 can be produced by combining the Stratasys' Tango material like TangoBlackPlus FLX980, with a rigid resin from the Vero family such as VeroWhitePlus RGD835.

Bartlett et al. (2015) directly printed the functional body of a combustion-powered soft robot using the digital materials with stiffness gradients that range over three orders of magnitude (1 MPa to 1 GPa) (Figure 4a). The stiffness gradient design allows the transition from soft to rigid components which minimized stress concentration at the interface of the two materials. The gradient top robot has shown high resilience and good performance and did not suffer significant damage due to brief exposure to the flames and elevated temperatures. Bellowed-type actuator design is one of the most common soft robotic designs that utilizes the multi-material material jetting process technique (Drotman et al., 2017, Zatopa et al., 2018, Kalisky et al., 2017, MacCurdy et al., 2016, Zhang et al., 2019). This is because the bellowed design can reduce the resistance to bending of the module compared to simple straight tube geometry. Digital materials, which are a mix of Tango and Vero materials from Stratasys, were used to fabricate the bellowed soft actuators in these studies. These bellowed components could be assembled and formed the quadruped robot's soft legs, performing challenging locomotion to walk over unstructured terrain using multi-directional actuated bending. Zatopa et al. (2018) used the digital material FLX9750, a blend of the Tango and Vero materials to fabricate a hydraulic control valve. In addition to the 3D printed elastomeric body, electrorheological (ER) fluid was used as a working fluid and gallium-indium-tin liquid metal alloy was used as electrodes to develop a soft octopus-like robot.

The commercial resins from Stratasys have been investigated and confirmed to possess shape memory capability in previous research (Qi et al., 2014, Yu et al., 2015, Joanne Ee Mei et al., 2017). Using the hybrid multi-material 3D printing techniques of material jetting and DIW, Zhang et al. (2019) has fabricated the fast-response stiffness-tunable soft SMP actuator and demonstrated its high load capacity and good shape adaptivity by a robotic gripper that can grasp and lift various weights and shapes. The soft actuator was made up of an assembly of multi-material actuator body and DIW printed conductive circuit on top of the shape memory polymer (SMP) slices which are printed with Agilus30 and VeroClear using PolyJet. The deformable conductive circuit was printed using silver nanoparticles to improve the rate of heating and cooling for faster softening-stiffening of the SMP. This study has shown the potential to combine various AM techniques to directly produce SMP actuator with printed conductive circuits. Rossiter et al. (2009) presented a two-membrane antagonistic actuator fabricated by the Stratasys PolyJet printer. All the dielectric actuator membranes and ancillary components were almost fully 3D printed in this study using the Tango and Vero materials. Despite the high-resolution structures produced, the printed elastomer could not perform on par to commercial dielectric materials in terms of its mechanical and electrical integrity.

Using a drop-on-demand piezoelectric inkjet system, 3D printing of thermal and UV-cure dielectric elastomer actuator (DEA) was developed (David et al., 2017). DEA membranes as thin as 2 μm possess good mechanical and actuation performance (actuated up to 130 V μm^{-1} at 2.4% strain) as compared to PolyJet material which has a low breakdown strength of ~60 V μm^{-1} without pre-strain. Similarly, a commercial service provider, ACEO (ACEO, 2018) developed the proprietary silicone printing process based on a drop-on-demand principle. Using the ACEO technology, Heung et al. (2019) 3D printed a soft robotic hand for providing rehabilitation training. The robotic hand consists of elastomeric-based actuator body which was directly printed from ACEO using silicone that has 30 shore A hardness and then reinforced with double-helical fiber wrapping, to withstand large deformation and input pressure. The results showed that the possible flexion angle of the finger is 137° and could produce a tip force of 2.45 N at 160 kPa, which are both sufficient to perform grasping and gripping activities.

Even though the design of the PolyJet-printed soft robots demonstrated high functionality under bending, twisting and stretching due to its superior lateral resolution of 50 µm, it has been identified that the existing 3D printed material still limits the compliance and robustness under fatigue (Rossiter et al., 2009, Zatopa et al., 2018, Drotman et al., 2017). As commercial PolyJet currently offers only limited proprietary elastomer material, researcher has taken the approach to custom made a UV-assisted rotational multi-head inkjet printing system to print polyurethane and epoxy (Jahan Zeb et al., 2016). This process was used to fabricate a multi-material tri-legged soft robot inspired by a spider. Soft legs were configured and printed in two halves using polyurethane and epoxy, as shown in Figure 4b. With the use of biometal filament (BMF) as the actuator, the tri-legged 'soft-bot' that can be controlled and paced via external electrical signals. Unlike the previous case whereby printing has to be paused to insert additional components like wires or conductive ink, the BMF wires can be placed directly on the desired locations by using the additional configured header to fully automate the fabrication of the soft robots.

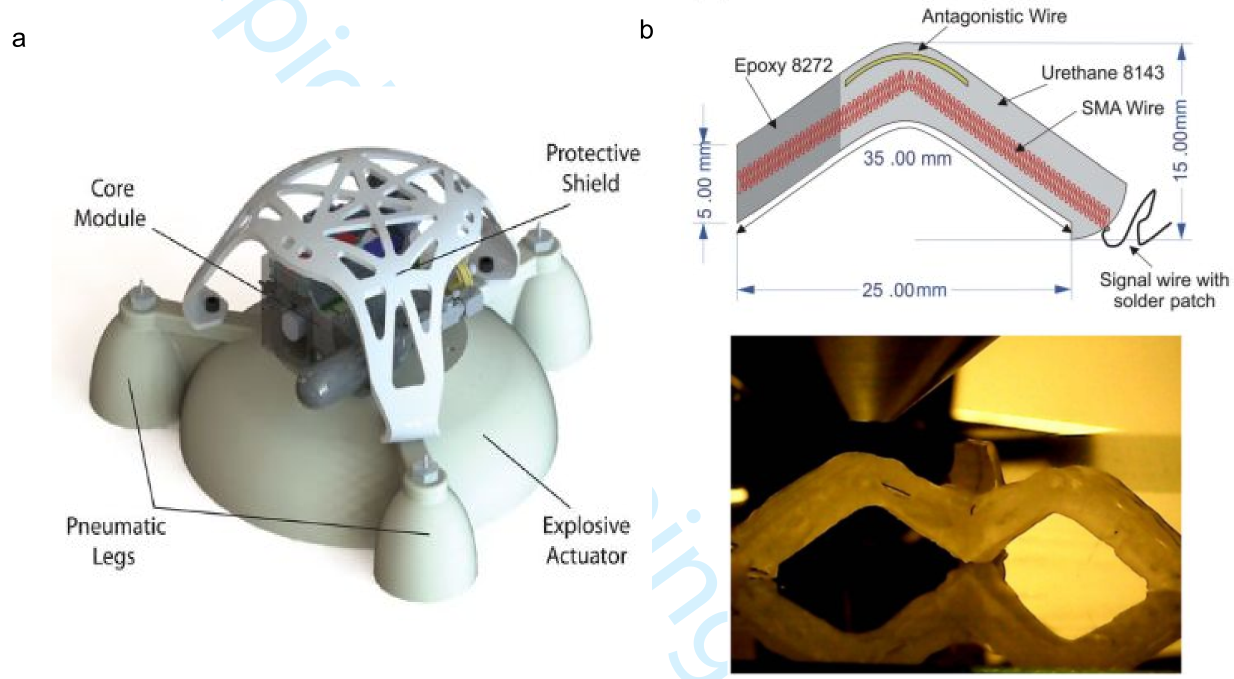

Figure 4 Examples of soft robotics fabricated by material jetting technique: (a) A gradient stiffness soft robot powered by combustion (Bartlett et al., 2015) (b) Tri-pedal soft robots printed using two flexible materials (epoxy and polyurethane) by a customized rotational multi-head printing system (Jahan Zeb et al., 2016)

2.5. 3D Printing Materials for Soft Robotic Applications

The 3D printing materials used for fabricating soft robots have been discussed in previous sections. The printable materials can be categorized into 5 categories: elastomer, flexible or elastic material, smart composite, shape memory polymer, and shape memory alloys, as shown in Figure 5. The typical materials used are listed in Figure 5. Soft materials are essential in the fabrication of soft robots as they need to be flexible and elastically deformable. Hence silicone, TPU, and hydrogels are the most commonly printed materials used for soft robotic applications. These materials are usually used to fabricate pneumatic actuated soft robots because of the highly deformable soft body that can bend and expand easily with low pressure. On the other hand, though PA 12 is intrinsically stiff, and requires a large force to deform, it is still being used to fabricate pneumatic-actuated soft robots (FESTO, 2012). This is mainly because when printed in relatively low wall thicknesses, PA 12 is considerably flexible while possessing good toughness and fatigue resistance properties. Shape memory polymer (SMP) and smart composite have unique properties as they could have variable stiffness under different operating conditions. For instance, the electroactive polymer exhibits large deformation in response to the electric field (Han et al., 2018a) and printed SMP is rigid below its glass transition temperature (T_g) but would become elastomeric when it is heated above T_g (Choong et al., 2017).

Materials including elastomers, flexible/elastic material as well as shape memory polymers, can be easily processed and printed directly with controlled parameters using conventional techniques. On the other hand, smart composite, for example, magnetorheological (MR) fluid, requires external application of magnetic field to the flow direction of the ink via a permanent magnet or an electromagnetic coil placed around dispensing nozzle, to impart a permanent magnetic moment to the extruded ink (Kim et al., 2018). Also, to print multiple materials simultaneously, multiple extruders or printing heads are needed (Jahan Zeb et al., 2016, David et al., 2017, MacCurdy et al., 2016). Similarly, the deposition of dissimilar material such as shape memory alloy (SMA) within elastomer requires the use of another deposition head (Jahan Zeb et al., 2016).

However, due to the incompatibility of the material and printing technique, some materials that could not be directly printed within a single system, have to be injected, added, or assembled to the final printed components. Some examples are wrapping the soft tubular actuator using fibers (Morrow et al., 2017), deposition of thin PVC layer in-between printed parts as stiffness augment unit (Mutlu et al., 2016), printing silver nanoparticles using DIW onto printed parts (Zhang et al., 2019), inserting SMA into printed parts (Han et al., 2018c, Umedachi et al., 2013) and injection of the electrorheological fluid (Zatopa et al., 2018).

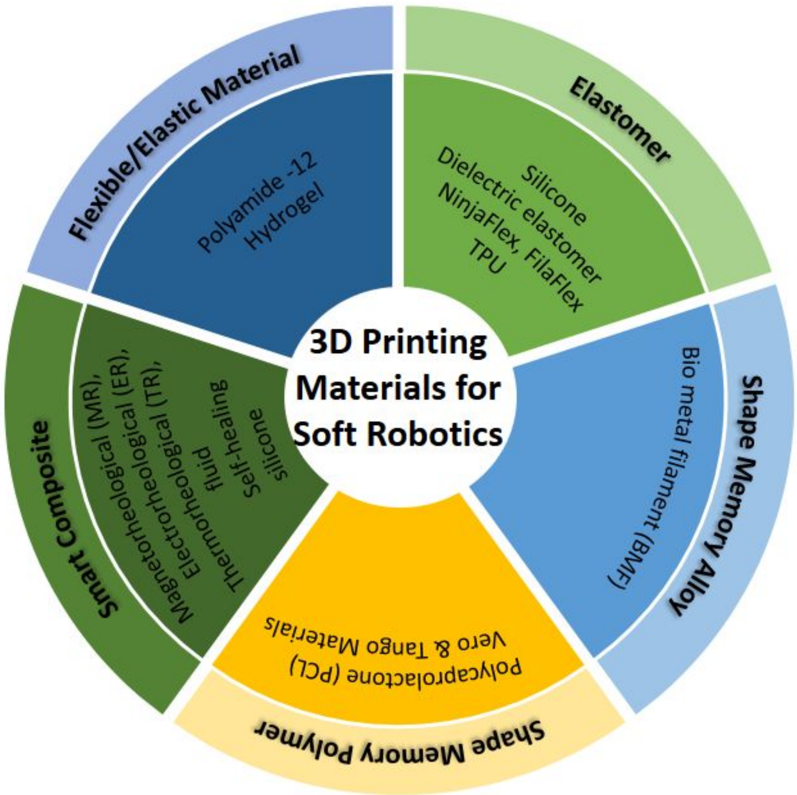

Figure 5 Five categories of 3D printing materials for soft robotics

3. Challenges

3.1. Resolution and Repeatability

The nozzle diameters determine the resolution of FDM and DIW techniques. Larger nozzle diameters might lead to poorer resolution. In addition, the thermofluidic behavior of the ink is also one of the key issues to ensure the resolution and repeatability of the printing, and this directly determines the speed of movement of the nozzle, material flow rate and microstructures of the printed part. Among the polymer 3D printing techniques, commercial SLA and material jetting printers generally have higher resolution and accuracy than the FDM and DIW printers.

Similar to conventional fabrication techniques of soft robots of multi-steps molding and curing, the repeatability of the production could also be an important issue for 3D printing techniques due to the elasticity and complex internal channel geometry. Nevertheless, repeatability issues for 3D printing could be alleviated with optimized printing parameters for each material used and thereafter building with consistent printing parameters and environment.

The resolution of the 3D printing technique is often inversely proportional to the build speed. One of the solutions to maintain both the print speed and resolution is to resort to multi-nozzles and multi arrays of print heads that can deposit multiple streams of ink at the same time. Using multiple nozzles and print heads also could introduce the opportunity to deposit disparate materials for multi-material printing, for instance, functionally graded structures produced by PolyJet (Tibbits, 2014, Oxman, 2011) and epoxy and polyurethane soft robot (Jahan Zeb et al., 2016).

3.2. Scalability

Many of the 3D printing techniques introduced earlier have small build volume and slow printing speed as most of them are built for research purposes. Despite having the advantage of being able to produce an integrated assembly of multiple components using 3D printing, the allowable build size of the 3D printer might force the designer to create modular components instead of printing entire soft robots at one go. It is also difficult to scale up the production or print platform as there are issues with post-processing like curing and removal of support material, as well as the trade-off between speed and resolution.

3.3. Material Fatigue, Anisotropy, and Degradation

Soft robots are generally composed of fluids, gels, and other deformable materials. Materials should be stretchable and have relatively small Young's moduli that match those of soft tissues. As soft robots must undergo repeated loading and unloading cycles, the material should have high toughness and resilience and can operate within its elastic regime. In addition to having high ultimate strain, the material should possess high resistivity to failure and fatigue. However, there are limited soft materials that can be printed at the current stage, and even fewer could fulfill these requirements.

The life cycle of an elastomeric soft actuator depends on the fatigue behavior of the material. Several studies, however, have highlighted that 3D printed commercial elastomers commonly have poor fatigue properties. Jacob and Christopher (2015) have investigated the fatigue characteristics of PolyJet printed elastomers and found that with a testing frequency of 1.7 Hz, the elastomers had closed to 10^6 cycles of fatigue life under low strains of 20% elongation or less. However, the elastomers have very poor fatigue properties at higher strains, (10^2 to 10^3 cycles for 40% - 60% strain) and have about 70% maximum strain to failure. A study by Dämmer et al. (2019) has also shown that the bellow soft actuators printed by PolyJet have poor fatigue properties. This effect is accentuated when the bonding in between printing layers is weaker for thin-walled bellow actuators. Bryan et al. (2015) carried out the fatigue test on the DLP-printed Spot-E elastomer, revealing that the elastomer fails after 9 ± 3 cycles, when subjected to 125% strain.

3D printing will also introduce anisotropy into the printed parts. The layer-by-layer fabrication approach used by AM techniques would cause the material to have a thermal gradient during printing, resulting in poorer properties across layers. Formation of voids due to improper deposition of soft material will also occur, leading to higher porosities and lower mechanical integrity of the printed parts as compared to the design values. This effect would also become aggravated in printing soft materials that have relatively low mechanical strength.

Many of the 3D printed materials, especially photocurable materials, are susceptible to UV degradation. Though shore hardness of the SLA materials did not show significant change after UV radiation and humidity aging, Young's modulus of the SLA material increases significantly, indicating the hardening of the material (Tröger et al., 2008). Also, there is significant shape distortion and color change after humidity and UV aging.

3.4. Support Structures and Materials

Printing with soft materials is exceptionally challenging without the use of support materials as soft material tends to deform under its own weight during build as the preceding layers are unable to support the weight of the following layers. Printing support structures or materials increases not only the manufacturing complexity and the production time and cost, but also the risk of damaging the delicate 3D printed components during support removal (Oropallo and Piegl, 2016). In addition, as shown in Table 1, bellow and tubular structures, which are usually thin-walled and hollow, are some of the typical designs for 3D printed soft robotics. This poses difficulty to the removal of support materials and structures for hollow structures printed using the FDM/FFF method since supports are usually removed manually. Various studies have in turn use the bridging method for FDM/FFF printing to print the top or roof overhanging layers of hollow structures, without using support structures or support materials (Yap et al., 2016). Another solution for printing hollow channels or overhangs with soft materials is to use sacrificial supports that can be dissolved or chemically removed (Hamidi and Tadesse, 2020). The support materials that can be dissolved by melting or soaking in solvent bath, as well as the trapped powder within the PBF parts could be removed from the inlet opening of the hollow pneumatic actuators.

4. Potentials

4.1. Sensors

Soft robots require flexible or stretchable sensors for monitoring and closed-loop controls. Despite the emergence of soft actuators, limited soft robots possess sensing capabilities to enable real-time monitoring and measurement (Yeo et al., 2016). Some of the flexible sensors that have been employed in soft robots include resistive, magnetic, capacitive and optoelectronic sensors (Li et al., 2017). Currently, most of the fabrication of flexible sensors within the fluidic elastomer actuators (FEAs) is based on embedment of conventional rigid electronics in flexible substrates (Luo et al., 2017, Jonathan et al., 2003), flexible sensors made up of aqueous ionic conductors (Chossat et al., 2013, Robinson et al., 2015, Larson et al., 2016, Truby et al., 2018), conductive liquid metals (Morrow et al., 2016, Chossat et al., 2013), conductive nanoparticle-filled polymer composites (Pinto et al., 2017, Yeo et al., 2016). Direct 3D printing of sensors onto the soft matrices could shorten the fabrication process and enhance the sensing capabilities. Truby et al. (2018) demonstrated a seamless integration of multiple ionically conductive and fluidic features within elastomers to create soft somatosensitive actuators (SSAs) via multi-material embedded 3D printing. Multiple complex networks of sensors including curvature, inflation and contact sensors, were directly printed into a soft robotic gripper, demonstrating the potentials of direct 3D printing of sensors into soft actuators.

4.2. Silicone printing

Soft robots articulate their entire body structure as a continuum so the body should be made of highly compliant materials with low Young's modulus such as an elastomer to minimize the force required to cause deformation. Silicone is one of the most commonly used material for fabricating the soft robot body structure due to its low modulus that permits large elastic deformation with very low force (Kim et al., 2013). Silicone, as compared to other thermoplastic elastomers (TPEs) available for 3D printing, has generally higher strain limit, durability and chemical resistance to solvents, and is biocompatible. It is also shown that silicone could achieve ultrahigh compression and extension, at least 4 times higher than the other 3D printed elastomers when it is used for producing the same soft robotic actuators (Goswami et al., 2019).

Though silicone printing is highly sought after in many industries especially biomedical, silicone 3D printing technique is not yet mature. Due to the curing mechanisms and high viscosity of silicones, printing soft materials like silicone often faces major problems such as the significant slumping under its own weight when the silicone is not cured immediately upon deposition, and material accumulation and clogging at the nozzle (Porter et al., 2017). As a result, it is highly challenging to print silicone with high accuracy and high repeatability.

Nevertheless, there has been remarkable progress over the last few years in the development of silicone 3D printing using direct ink writing method (Mannoor et al., 2013, Duoss Eric et al., 2014, Wu et al., 2017, Schaffner et al., 2018, Morrow et al., 2017, Yirmibesoglu et al., 2018, Hamidi and Tadesse, 2020), UV inkjet printing (David et al., 2017, Jahan Zeb et al., 2016), thermal cured inkjet printing (David et al., 2017), binder jetting (Liravi et al., 2017), stereolithography (Kim and Tai, 2016, Wallin et al., 2017) and aerosol jetting (Reitelshöfer et al., 2016). There is also a new freeform reversible embedding (FRE) technique to print silicone without the need for support by extruding catalyst onto a bath of silicone oil (Tom Fripp, 2016). Also, based on the UV inkjet printing process developed by Wacker Chemie AG (Ernst Selbertinger et al., 2017), a commercial service provider, ACEO (ACEO, 2018), also offers 3D printing service for silicone that is comparable to injection molding. Carbon, which owns the proprietary CLIP process that is based on vat photopolymerization, also develops a silicone resin, SIL 30, for printing tear-resistant and biocompatible products (Carbon, 2020). The development of silicone 3D printing will help to streamline the fabrication of soft robots and even create the opportunity to explore other design variations that were not possible using traditional fabrication methods.

4.3. 4D Printing and Shape Memory Polymers

The term '4D printing' refers to the process of building 3D printed smart materials or components, using stimuli-responsive composite or multi-material with varying properties, demonstrating physical or chemical change of state through time upon reacting to stimuli. Many 4D printing research utilizes the multi-material capability of PolyJet to produce the smart structures including self-evolving structures (Raviv et al., 2014) and self-folding structures (Qi et al., 2014, Ge et al., 2013, Yu et al., 2015, Joanne Ee Mei et al., 2017, Tibbits, 2014) by using materials with different hydrophilic and thermal properties. Through the controlled and pre-determined deposition of each material at specific locations, the smart structures can be programmed and perform the shape recovery upon external stimuli is being applied. Qi et al. (2014) utilized the materials with different thermal properties to develop 4D printing structures with varying designs including multi-layer laminates (Ding et al., 2017) and two-layer fiber-embedded laminates (Wu et al., 2016, Ge et al., 2013), as shown in Figure 6. The design concept of elastomer with fibers embedment can also be a potential candidate to replace the existing fiber reinforced soft actuators which are usually fabricated by laborious multi-step curing of elastomer and manual winding of fibers.

4D printing can also be achieved through 3D printing of shape memory polymer (SMP). Shape memory polymers are programmable smart polymeric materials that possess the ability to return from a deformed or temporary shape to their original and permanent shape, upon induced by an external stimulus. Recently, there has been substantial progress on developing 3D printable SMPs, including the use of SLA to print single material glassy SMP (Choong et al., 2017) and multi-material SMPs (Ge et al., 2016), the use of DLP technique to print SMP with self-healing properties (Invernizzi et al., 2018), as well as the use of UV-assisted DIW technique to print elastomeric SMP with self-healing capability (Kuang et al., 2018) and SMP with nanocomposites that possesses magnetically guidable properties (Wei et al., 2017). There is also recent research to print shape memory polymer, graphene polylactic acid (PLA) using FDM method onto a paper substrate to create electrical/thermal actuated paper actuator that has various sensing capabilities including angle control, touching and sliding, as well as various actuation methods including curve, sharp and pattern folding (Wang et al., 2018). The unique characteristics of SMP and 4D printing could enhance the functionality of soft robots by having multi-material smart structures that allow the designers to have precise control. Instead of using the time-consuming multi-step molding processes to fabricate the fiber-reinforced soft robotics, it can be easily printed using the multi-material printing technique while demonstrating predictable motion upon pressurization (Yap et al., 2018).

4.4. Functionalized materials and structures

Several 3D printing methods have been developed to program the materials' stimulus response during printing instead of relying on the mechanical programming after fabrication of the SMPs. Functionalized materials and structures are enabled by 3D printing through programming both the print path, print orientations and the printed material microstructure to achieve the shape changing or shape morphing effect. By varying the print speed and nozzle diameter in the direct ink writing of hydrogels, the extent of shear-induced alignment and hence the magnitude anisotropic swelling can be controlled and predicted (Sydney Gladman et al., 2016). Similarly, liquid crystal elastomer (LCE) printed using the DIW technique also exhibited controlled molecular alignment with the print path, through intrinsic shear force imposed during ink deposition (Ambulo et al., 2017). In another study using the DLP technique, when subjected to different durations of light exposure, different swelling ratios were produced in the hydrogels, generating different localized stress for shape morphing within a printed object (Huang et al., 2016). These studies have shown that the material anisotropy as a result of varying printing parameters could be utilized to generate various controlled motions or movements. These smart materials and structures can be used directly without the need for additional programming, saving time and manpower. The functionalized materials could also provide additional design space for creating shape shifting or morphing designs for soft robotics.

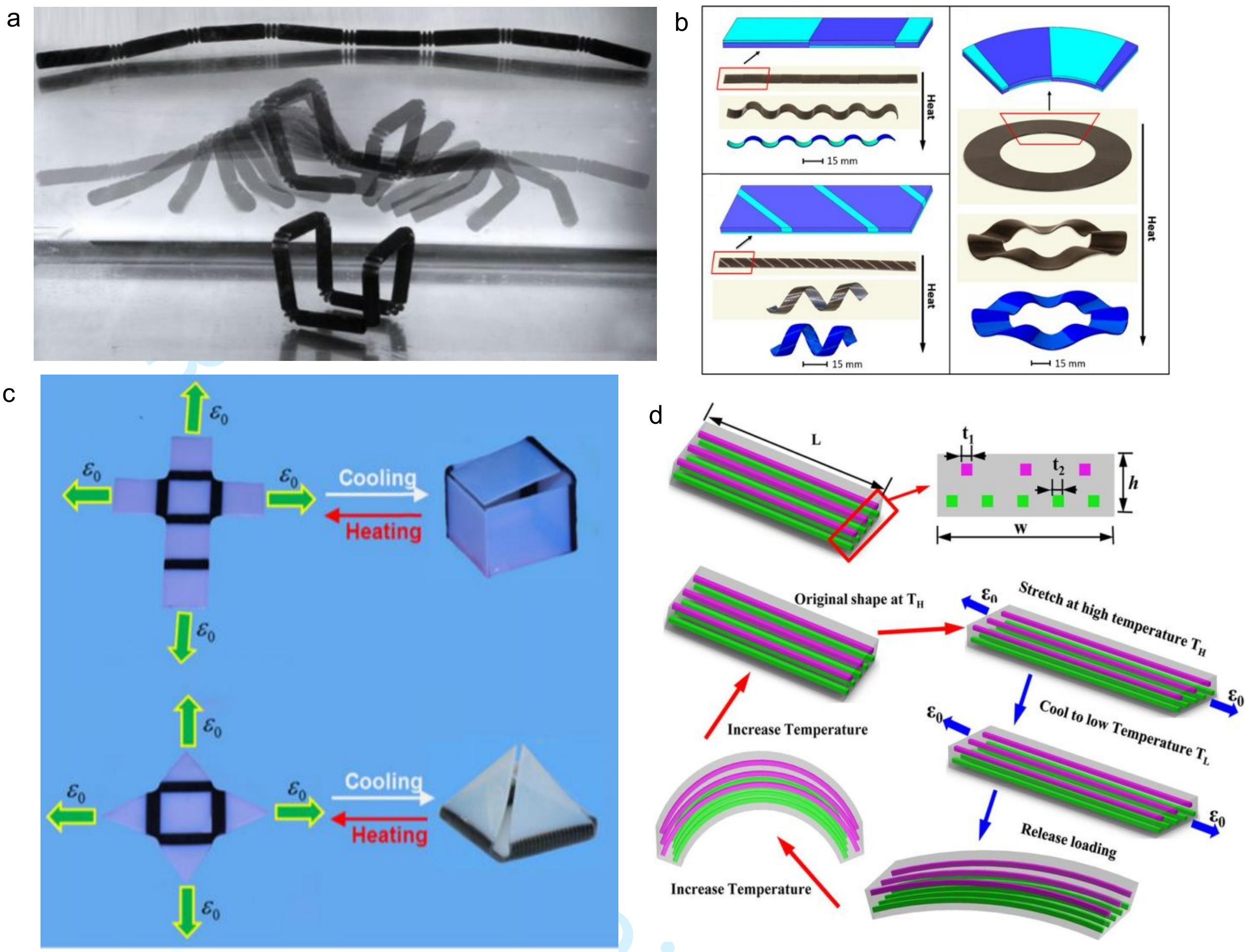

Figure 6 Examples of 4D printing: (a) Transformation from one-dimensional strands to two-dimensional structures after the soft material expands and moves upon encountering water (Tibbits, 2014), (b) The shape transformation of 4D printed structures as printed and after heating (Ding et al., 2017), (c)self-folding smart structures into three-dimensional structures upon heating and cooling (Qi et al., 2014), (d) Thermomechanical programming procedures for the composite strips to achieve multi-step deformation (Wu et al., 2016)

5. Future Outlooks and Conclusion

Various 3D printing techniques have introduced multi-material printing capability by employing multiple nozzles or print heads in DIW, FDM, and material jetting techniques, switching of vats in the vat photopolymerization technique. These have demonstrated the potentials in building functional soft robots composed of materials with disparate physical, mechanical, electrical, magnetic, optical properties. Another fabrication strategy is to combine different 3D printing technologies to direct fabricate all the soft robots' critical components including actuators, sensors, controls and power systems in a single process.

The issues with the anisotropy in the 3D printed materials and the weak interfacial bonding between different materials might result in unpredictable motions and premature failures. Degradation and poor fatigue life of 3D printed elastomers could also limit the service life of 3D printed actuators. In the process of development of new products including soft robotics, 3D printing also generates a large amount of waste for test prints, failed prints, and unwanted prototypes, Most of the polymers, for example, support materials, unused resins, highly crosslinked photocurable 3D printing materials, and the mixed materials, cannot be recycled directly and could cause serious environmental pollution. It is of great significance to also develop degradable 3D printed soft materials to enhance the sustainability of 3D printing.

Current material availability and intrinsic material characteristics are the biggest hurdles for the usage of 3D printing in soft robots. Despite that the recent work done in 3D printed soft robotics is still limited to experimentation and prototyping, additive manufacturing could ultimately be used for the end-use and production of soft robotics. With the development of printable functional materials, 3D printing will greatly facilitate the direct fabrication of the end-use soft robots with sophisticated designs and functions, for instance, through the printing of sensors onto smart materials.

Conflict of Interest

The authors declare that they have no conflict of interest.

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