A Review of 3D-Printable Soft Pneumatic Actuators and Sensors: Research Challenges and Opportunities

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The soft robotics field is changing the way people think, build, interact, and most importantly perceive robots. Robots have long been perceived as machines made of metals that their sole purpose is to perform repetitive tasks in isolated environments. Herein, the recently developed soft pneumatic actuators and sensors that are fabricated using additive manufacturing techniques and in which the fluid used for actuation and sensing is mainly or solely air are focused upon. This review presents the soft pneumatic actuators and sensors in terms of their types, materials, fabrication techniques, capabilities, and applications. Also, it offers a discussion on the presented 3D-printable soft actuators and sensors along with a list of what is needed to develop robust and functional soft actuators and sensors for soft robots and how such robots will evolve in the future. This article is expected to stimulate more interaction between materials scientists and robotic researchers to synthesize soft and functional materials that meet application, function, and user requirements, in a way to implement a top-down approach to shorten the path between science and application of soft smart materials and their use in establishing functional soft robotic systems.

1. Introduction

1.1. Hard and “Soft” Robotics

Robotics can be defined as the science and engineering of systems and devices, which are reprogrammable, multifunctional, multipurpose, adaptable, and versatile, and intelligently use sensing for action.[1] Traditional robotic systems and devices are commonly made of several rigid links connected with a single degree of freedom (DoF) rigid or elastic joints, where each joint is controlled independently to realize a task or purpose.[2] However, such conventional robots are still limited to factories where they conduct tasks requiring high precision, accuracy, and speeds, as well as large forces,[3] using intricate algorithms that control either their position (i.e., each link and whole robot) and/or the contact forces during their physical interaction with their environment.[4] These systems cannot operate safely alongside humans in unstructured environments due to the lack of compliance in their structure.[5] To overcome these safety limitations, and to bring robots and humans together as task partners, the soft robotics field has emerged to develop soft robots that can interact safely with delicate environments better than conventional robots.[5] Thus, the definition of robotics can be expanded to soft robotics, which is defined as the science and engineering of robots that are mainly made of soft and compliant materials, components, and monolithic active structures.

Compared with conventional robots, soft robots can safely interact with and adapt to their immediate environment.[4,6] We compare hard and soft robots in terms of their characteristics and features, as shown in Table 1, to show the main differences between them. Similarly, in Figure 1, we show a comparison between a rigid-bodied hyper-redundant robotic arm and a corresponding soft robotic arm to show the main differences between conventional robots and soft robots. Figure 1 shows that a soft robotic system should have the same elements involved in conventional hard robotic systems. However, it must be designed in such a way that all essential elements should be built and placed into the same monolithic body similar to living bodies like humans, animals, and plants.

1.2. Advantages of Soft Robotics

Soft robots which are sometimes called biologically inspired robots[7] have multiple advantages compared with traditional robotic systems.[1,5] First, soft robotic systems are composed of soft and deformable passive materials that allow them to safely interact with humans and delicate objects and be deployed in unstructured environments.[8] Also, diverse low-cost, soft, stretchable, and flexible smart materials and electromaterials can be used in soft robotic systems to make them intelligent, accessible, and affordable.[8] Such robots offer unique solutions for robotic applications that involve smooth touches, safe interaction with humans,[9] and grasping and manipulation of delicate
Second, soft robots are made of soft monolithic bodies containing actuation elements, sensing elements, compliant or deformable mechanical structures, energy-storage units, and electronics with a minimum footprint. Therefore, these systems require minimal or no assembly processes in some cases.

Third, soft robots can be directly fabricated using various additive manufacturing technologies to fabricate soft robots with embedded actuation and sensing capabilities. Fourth, soft robotic systems can be used and implemented in diverse robotic applications such as grippers, locomotion robots, humanoid objects. Second, soft robots are made of soft monolithic bodies containing actuation elements, sensing elements, compliant or deformable mechanical structures, energy-storage units, and electronics with a minimum footprint. Therefore, these systems require minimal or no assembly processes in some cases.

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robots, medical robots, wearable robots, human–machine interfaces, and many others where they can interact safely with delicate and dynamic environments without requiring complex control algorithms.[1,4,5] Fifth, the compliance of soft robots makes them ideal for handling extreme external mechanical deformations.[13] Finally, soft robotic systems can change their overall compliance to deliver a desired or required force, especially when operating in environments where humans are in the loop.[14] Therefore, their structural and mechanical behavior is not fixed as in conventional robots but adaptive. Although soft robots have several advantages, it is important to note that they cannot replace conventional robots. However, soft robots are ideal for certain applications such as gripping, locomotion, and medical applications where the environment is highly dynamic and sensitive to physical interaction.

1.3. Challenges of Soft Robotics

It is highly desired that a soft robot is made primarily or even completely of soft materials. The mechanical structure, actuators, sensors, electronics, and power sources of such robots should be soft, deformable, and compliant, and if possible, they should be unified in the same monolithic soft body (Figure 2).[1] However, the realization of completely soft robotic systems is very challenging and requires joint efforts between scientists and engineers to combine soft and deformable actuators, sensors, controllers, electronics, and power supplies in one autonomous soft system.[15] In addition, the soft robotics field faces some challenges associated with design automation tools for modeling (i.e., simulating) and design optimization and fabrication of soft topologies.[16,17] Modeling is essential to design and establish novel soft robots.[11a] However, it must noted that numerical methods are popular for the design and development of soft robots due to nonlinearities and challenges associated with deriving analytical models.[11a]

Intensive research is being conducted to develop soft and compliant structures, central processing units or controllers, power supplies, sensors, and actuators for soft robots. For example, soft and compliant materials such as silicone and other elastomers are being used to develop the main structure of a soft robot.[3,8,6b] Also, central control units and sensing elements[18] such as soft electronic skins (e-skins)[19] can be made stretchable and flexible due to the advancements in the field of soft electronics.[3,20] Also, stretchable batteries are progressing toward developing high energy density and compliant power supplies that are suitable for powering soft robotic systems.[21] Also, finite element modeling (FEM) is being used as one approach to model and simulate soft robots and their actuators and sensors. There are numerous reasons for this:[22] First, FEM can accurately and quickly predict the behavior and performance of soft robotic systems, for a specific stimulus such as pressure, force, displacement, and others, prior to their fabrication. This saves significant design and optimization times and fabrication resources. Second, FEM is very effective in optimizing and modifying the geometry or topology of soft robotic devices such that they meet certain design and performance requirements.[22,23] The simulation data can be efficiently used to iterate between possible designs to determine the design with the most suitable behavior and performance. Finally, FEM allows to accurately and efficiently control soft robotic systems.[24] There are several

Figure 2. An illustrative schematic showing the materials and methods required to develop completely soft and untethered autonomous soft robots along with the primary soft components that constitute them and their potential applications.
FEM software such as SOFA, Abaqus (Dassault Systèmes Simulia Corp), COMSOL Multiphysics, and ANSYS (ANSYS Inc.) that use a range of models for hyperelastic materials to obtain highly nonlinear simulations to predict and optimize the performance of soft robots. It may be noted that lumped parameter modeling, point lattices connected by linear beam elements, and Cosserat elements can be used to model soft robotic systems.

The development of innovative soft, functional, smart, and most importantly 3D-printable materials directly determines the progress in soft robotics to establish soft robots. Soft active, living, robotic, and/or responsive materials are vital to developing functional and responsive soft robots. Further, the mechanical and electrical properties of such materials are important for a soft robot to establish safe contact with its immediate physical environment. Instead of using complicated and laborious force control techniques that are typically used in hard robotic systems to establish safe contact with their environment, the controllable properties of such materials can be well exploited to safely conform and interact with any environment.

1.4. Soft Actuators and Sensors

Soft actuators and sensors are the most critical elements of a soft robotic system. The soft actuators that can contract, extend, bend, and/or twist with favorable relative precision while delivering sufficient output forces should be dexterous, fast, and reversible. Moreover, soft robotic systems require highly sensitive, reliable, repeatable, stretchable, and flexible soft sensors that can sustain and detect various modes of deformations such as extension, contraction, bending, and twisting to complete and support the operation of the soft actuators. Such robust soft sensors are highly desirable to build reliable feedback control systems and machine learning tools for soft robotic systems.

1.4.1. Soft Actuators

The primary and most critical stage in the development of a soft robot is the selection and design of the soft actuation concept. The size, weight, performance, type of sensors and their location, control architecture, and power requirements of a soft robot are directly influenced by the type and design of the soft actuator involved in the soft robot. The development of novel soft, dexterous and functional actuators that can be manufactured using either additive manufacturing techniques or conventional molding and casting techniques directly affects the progress in soft robotics. Actuators convert an input stimulus into a useful mechanical output. Depending on the type of the soft actuator, the input stimulus can be chemical species for electroactive polymer actuators, air for pneumatic actuators, liquid for hydraulic actuators, heat for shape memory polymers and alloys, light for light-responsive actuators, electrical field for dielectric elastomers, and magnetic field for magnetorheological fluids and polymers. Smart materials and structures including shape memory alloys, dielectric elastomers, ionic polymer–metal composites, coiled polymer fibers, hydrogels, humidity-responsive materials, and magnetic responsive structures have been used to build soft actuators. Also, chemical reactions such as combustion, electrolysis, and catalytic reactions were used to power and drive soft robotic systems. Likewise, phase-change materials such as water and wax were used to generate driving internal pressures for soft robots. Moreover, underactuated and adaptive tendon-driven soft grippers were developed and powered by electric motors. Pneumatic actuators as one of the most common actuators used to drive and operate soft robots were also developed. The major positive pressure pneumatic actuators for soft robots include McKibben actuators, fiber-reinforced actuators, and PneuNets. In addition, another class of soft pneumatic actuators activated using negative pressure uses particle jamming to achieve a conformal grasp. Similarly, negative pressure was used to drive and operate diverse actuators and soft robotic systems.

1.4.2. Soft Sensors

In this Review, we consider a typical soft robotic system with a continuum topology embodying all of its essential elements (Figure 1). This follows that the sensing concept will be based on the elongation and contraction (i.e., strain) of the material responsible for actuation. This internal strain can be measured using a change in resistance and/or capacitance, depending on the arrangement of the actuators and sensors in the monolithic soft body. However, the exhibited strain must not exceed the maximum or ultimate strain of the sensor material and of course that of the actuator material to make sure that the sensing elements will last longer than the life of the soft robotic system. Another important requirement is that the sensor material should be more compliant than the surface to be placed on or the body to be placed in. This is also important for not creating mechanical resistance to actuation and for the sensing elements to stay stable over their full lifetime. The typical types of sensors used in soft robots are resistive and capacitive sensors. A resistive strain sensor is made of a conductive material and a stretchable base material filled with a conductive liquid. When a mechanical strain is applied, the whole structure stretches and subsequently the electrical resistance of the conductive film or conductive liquid changes, indicating the strain in the continuum body. On the other hand, capacitive strain sensors consist of a soft dielectric layer covered with stretchable electrodes, like a parallel plate capacitor. The change in the thickness of the composite structure due to a mechanical strain indicates the change in its capacitance and therefore, indicating the strain in the continuum body. In addition to the traditional strain-sensing mechanisms based on the change in resistance or capacitance, tunnelling effect, crack propagation in thin films, and disconnection between overlapping nanomaterials are new mechanisms to establish stretchable strain sensors. Although capacitive strain sensors have high linearity, stretchability, and low hysteresis, their sensitivity is low (i.e., very low gauge factor \( GF \leq 1 \)). On the other hand, the resistive strain sensors have a high sensitivity (i.e., high GFs) and stretchability. But they show a high hysteresis and nonlinearity in their response. Measuring decoupled strains remains a significant challenge when it comes to using soft resistive and capacitive sensors. Another challenge is to synthesize synthetic materials for strain sensors with high stretchability (strain \( \geq 100\% \)) and high sensitivity (GFs \( > 50 \)).
Numerous soft sensors have been developed for use in various soft robotic applications. However, the integration of such sensors into soft robotic systems and devices requires multiple and laborious fabrication steps. Resistive stretchable and/or flexible strain sensors such as flex sensors,[54] conductive inks,[55] ionic conductive liquids,[122a] liquid metals,[20b,56] fabrics and textiles,[57] highly compressive, sensitive, and biodegradable foam sensors,[58] resistive 3D printable thermoplastics,[59] and ultrathin piezoresistive sensors[60] incorporated in soft and deformable 3D-printable bodies[61] were established for soft sensing applications. Also, capacitive soft sensors that can be used as pressure sensors,[62] tactile sensors,[63] and strain sensors were developed for soft robotic systems.[64] In addition to resistive and capacitive soft sensors, other soft sensing technologies such as optical strain, curvature, texture, and force sensors for prosthetic hands[65] and optical tactile soft sensors with exteroceptive and proprioceptive sensing capabilities for robotic end-effectors[66] were developed. Also, magnetoelectric materials were exploited to develop self-powered soft tactile sensors,[67] and pneumatic sensing chambers based on soft deformable hollow structures were developed for human motion-monitoring systems,[68] force sensors,[69] and tactile sensors.[70]

In this Review Article, we focus specifically on soft pneumatic actuators and sensors that are fabricated using additive manufacturing techniques and in which the fluid used for actuation and sensing is mainly or solely air. This Article presents the 3D-printable soft pneumatic actuators and sensors in terms of their types, materials, fabrication techniques, capabilities, and applications.

2. 3D-Printable Soft Pneumatic Actuators

2.1. Actuation Types

Soft pneumatic actuators are based on a volumetric expansion or contraction which can be designed in several ways to generate a specific mode of deformation such as extension, contraction, bending, twisting, or a combination of them. In general, these soft actuators have a high power density and offer soft contact with high conformability. Such actuators are also lightweight, affordable, and easy to fabricate using conventional (i.e., molding and casting) and additive manufacturing techniques. Soft pneumatic actuators can be divided into two main classes including positive-pressure actuators and negative-pressure (i.e., vacuum) actuators (Figure 3). The main difference between these two classes is that positive-pressure soft actuators require compressed air to be activated or inflated (i.e., volume expansion) upon their actuation, whereas negative-pressure soft actuators require a vacuum source to be activated (i.e., volume contraction). Negative-pressure actuators are preferable to positive-pressure actuators in some applications due to many reasons. First, such actuators provide a fail-safe feature due to a negative pressure input.[71] This means that the actuators remain functional, under a continuous supply of vacuum, after failure where their performance is not affected by minor air leaks or structural damage. Second, these actuators shrink upon activation when compared with positive-pressure actuators that expand, which means that they can be used and deployed in confined spaces.[52b] Third, these actuators are more durable compared with positive-pressure actuators and therefore can operate for longer periods.

Figure 3. 3D-printable soft pneumatic actuators types, materials, fabrication technologies, and capabilities.
without structural failure. Finally, negative-pressure soft actuators are safer to operate alongside humans as they shrink in volume upon their activation compared with positive-pressure soft actuators which expand upon their activation and therefore are prone to exploding at high pressures. However, negative-pressure actuators are usually limited by the range of input pressures that can be applied to their internal structure, and therefore their performance is limited in terms of output force and total deformation which is not the case for positive-pressure soft pneumatic actuators.

2.2. Materials

Soft, stretchable, and flexible materials such as silicone elastomers that are similar to biological materials are desired to develop 3D-printable soft pneumatic actuators. The materials for soft robotic systems are expected to have the properties of biological materials. It is very important to develop smart materials to target specific robotic applications and function requirements. In other words, a “top-down” approach must be followed to formulate and develop the materials to establish function- and application-specific soft robotic systems (Figure 3). However, the materials synthesized will not be fully exploited or in some cases not used in robotic applications. This follows that material scientists and roboticsists must collaborate and come together so that the developed materials can be used in diverse robotic applications to advance the fields of soft robotics and functional materials. Synthetic materials with programmable mechanical, rheological, and electrical properties are required to incorporate morphological computation into the design of soft robots. Further, soft robots should be able to vary their overall stiffness or compliance to deliver a range of desired output forces and safely interact with different environments that have a range of stiffnesses and contact conditions. With variable mechanical compliance, a soft robot can establish a safe contact by distributing the contact forces on a larger contact area. This means that the contact pressure can be highly reduced and therefore, with this variable compliance, the robot can switch between different states, including a soft one where it is highly deformable and a rigid one where it can match the performance of hard robots which are made of materials with a bulk modulus of elasticity of at least 1000 MPa. It is important to note, for comparison purposes, that the living organs such as the skin, muscle tissue, and cartilage have a modulus of elasticity in the range of 100–1 GPa. Therefore, there is a huge difference between the compliance of hard robotic systems and soft and delicate environments that has to be addressed using proper control algorithms. This significant difference in compliance makes it clear why soft robots with programmable compliance can match the compliance of their close environments are desirable and better suited to safely and adaptively interact with soft environments. The compliance matching between a robot and its surroundings is important to have safe human-machine interactions.

The modulus of elasticity technically describes the softness or hardness of a uniform material which is fabricated in the shape of a prismatic bar to be subjected to an axial loading to generate solely elastic strains. Thus, the concept of modulus of elasticity should be cautiously used to describe the softness of soft robotic materials. But, it can be used to compare the relative softness of soft robotic systems with that of hard robotic systems.

2.3. Additive Manufacturing Technologies

The use of conventional manufacturing techniques that involve multiple fabrication steps to develop soft pneumatic structures is time-consuming as it requires multiple laborious fabrication steps and limits the development of soft actuators with complex geometries and topologies. Alternatively, 3D printing technologies can be used to directly manufacture soft actuators and prototype various designs rapidly and efficiently. 3D printing can be used to program the motion of soft actuators, produce soft robots with diverse capabilities, control the elasticity of soft and complex structures, and improve the performance and durability of soft pneumatic actuators. There are several additive manufacturing technologies such as fused deposition modeling (FDM), stereolithography (SLA), digital light processing (DLP), selective laser sintering (SLS), and material jetting (MJ) that can be used to 3D print soft pneumatic actuators using soft materials such as silicones and multimaterial printing with different properties and capabilities. Although 3D printing has several advantages when it comes to fabricating soft robots, in some cases, accessibility and affordability stand as major limitations of additive manufacturing technologies. For instance, while FDM 3D printers are low cost and therefore accessible, most of the other additive manufacturing technologies are expensive or not readily available for the community. Also, for the accessible technologies like FDM, some essential skills such as computer-aided design skills and 3D printing experience to model, design, and fabricate functional soft airtight pneumatic actuators are required. Finally, 3D printing a variety of soft materials with elastic moduli matching the ones of soft tissues that range between 3 kPa for stomal tissue and 900 kPa for cartilage is still a challenge.

It is essential to develop novel additive manufacturing technologies and polymer chemistries to address this challenge. To this aim, 3D-printed soft materials such as silicones and hydrogels are examples of printable materials for soft robotic applications that address such a challenge.

2.4. Capabilities

One of the main advantages of soft pneumatic actuators is that they can be 3D printed using smart, functional, and intelligent materials that provide them with various capabilities and functionalities (Figure 3).

2.4.1. Self-Healing and Fail-Safe Features

Biological muscles are characterized by their ability to self-heal after being damaged and even becoming denser and stronger when this cycle is repeated frequently. Similar self-healing capabilities are also desired for materials used to 3D print soft pneumatic actuators that rely on either positive or negative pressure to operate as any damage in their structure might lead to air

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leaks and therefore their failure. For instance, soft bidirectional bending actuators can rapidly self-heal and operate again after being punctured when sunlight is directed at their structure.\textsuperscript{[82b,c]} In addition, vacuum actuators are characterized by the ability to remain functional even after their rupture, under a continuous supply of negative pressure, and therefore they can be classified as fail-safe actuators.\textsuperscript{[71a,88]}

### 2.4.2. Scalable and Customizable Soft Actuators

The ability to fabricate soft pneumatic actuators using additive manufacturing techniques makes it possible to scale and customize their structures (i.e., internal volume) to target specific applications with specific requirements easily and rapidly. Microsized actuators can be easily fabricated to develop miniature soft robotic devices including grippers, artificial muscles, locomotion robots, and camouflaging robots.\textsuperscript{[82g,83c]} Similarly, macrosized actuators can be 3D printed and scaled either in terms of internal volume or in terms of the number of actuators assembled in one single unit to amplify their output force.\textsuperscript{[71a,91]}

### 2.4.3. Modular Soft Actuators

Soft modular actuators provide soft robots with various capabilities such as self-reconfiguration in which they can disassemble and reassemble to form new morphologies. Therefore, modular actuators can adapt to various environments and tasks and distribute actuation and sensing to improve their functionality and reliability that consequently lead to a decrease in their overall cost and maintenance cost.\textsuperscript{[92]} For example, modular pneumatic units can be 3D printed separately and assembled to realize soft actuators with variable length and DoF\textsuperscript{[23a]} or build various robotic devices.\textsuperscript{[93]} In addition, distributed actuation and sensing means that different configurations in the same soft robotic device can be considered to target specific requirements.\textsuperscript{[87,94]}

### 2.4.4. Programmable Multimodal Soft Actuators

Soft pneumatic actuators that can bend, twist, contract, and extend simultaneously can highly widen their usability in various applications requiring multiple modes of deformations to accomplish a specific task. For instance, soft helical actuators that can be programmed to generate bending and twisting motions simultaneously are well suited for enhancing the gripping performance as they can wrap around the handled objects.\textsuperscript{[81b]} Similarly, soft actuators can be programmed through 3D printing by exploiting their material properties and architecture to generate either a single motion or various motions simultaneously to target specific soft robotic applications.\textsuperscript{[77,86b]} Also, a desired motion can be achieved in 3D space using soft manipulators to accomplish a pick and place task, for instance, by activating a specific actuator from a bundle of connected actuators.\textsuperscript{[71a]}

### 2.5. Applications

3D-printed soft pneumatic actuators that can deliver useful output forces and various modes of deformation have several potential applications including adaptive grippers, parallel manipulators, locomotion robots, artificial muscles, assistive wearable devices, medical devices, and haptic feedback devices.

#### 2.5.1. Grippers and Parallel Manipulators

Soft adaptive and compliant grippers are ideal for grasping, picking, manipulating, and placing delicate and fragile objects in highly dynamic environments (Figure 4).\textsuperscript{[10]} Soft grippers that are activated based on 3D-printed soft pneumatic actuators can be used to grasp and pick heavy objects and a wide variety of objects with irregular shapes (Figure 4A,B)\textsuperscript{[71a,72,81a,95]} and fruits and vegetables (Figure 4C).\textsuperscript{[23a,91]} In addition, such soft robotic grippers can be composed of multiple fingers where in some cases they are built monolithically (Figure 4D,E,F)\textsuperscript{[78,81a,b,96]} based on the human-hand model to realize dexterous anthropomorphic grippers or robotic hands.\textsuperscript{[84b]} Also, 3D-printed soft pneumatic actuators can be used to achieve desired functions in grippers such as variable stiffness (Figure 4G,H)\textsuperscript{[89,98]} using a combination of positive and negative pressure actuators, pressure and/or position sensing (Figure 4I)\textsuperscript{[89,98]} for telemanipulation that involves haptic feedback in some cases,\textsuperscript{[99]} and modularity.\textsuperscript{[93,100]} Also, actuators that achieve multiple modes of deformation such as bending and twisting in 3D spaces were developed and demonstrated in gripping applications.\textsuperscript{[81b,101]} Also, improved 3D-printed actuators with reduced out-of-plane deformation\textsuperscript{[102]} and bioinspired compliant structures (Figure 4)\textsuperscript{[103]} were developed to enhance the grasping capabilities of grippers. Finally, hybrid grippers that incorporate soft pneumatic actuators along with rigid, soft, or semisoft structures can be developed\textsuperscript{[45,91,104]} 3D-printed three-finger grippers were developed to automate lunch box packing\textsuperscript{[105]} by studying grasping in soft grippers for food handling.\textsuperscript{[106]} Microgrippers were also 3D printed for gripping microsized objects (Figure 4K).\textsuperscript{[82g,83c]} 3D-printed parallel manipulators with multiple degrees of freedom are usually used to guide soft robotic grippers or soft end-effectors\textsuperscript{[107]} in space to grasp, manipulate, or pick and place objects. 3D-printed vacuum-powered parallel manipulators are developed and either coupled with soft suction cups for picking and placing applications\textsuperscript{[71]} or a laser pointer for handwriting applications.\textsuperscript{[88]} Soft 3D-printed manipulators can move in space by bending, extending, and contracting (Figure 4L).\textsuperscript{[86c,108]}

#### 2.5.2. Locomotion Robots

Soft locomotion robots\textsuperscript{[109]} are highly desired for applications (Figure 5) that require deploying robots in extreme and harsh dynamic environments where extreme conditions such as elevated temperatures, excessive deformations and pressures, impact forces, tiny and confined spaces (Figure 5A),\textsuperscript{[11]} and radiations (Figure 5B)\textsuperscript{[110]} are present. 3D-printed pneumatically actuated soft robots can be deployed in confined spaces for inspection applications.\textsuperscript{[71a]} Also, such soft locomotion robots are ideal to adapt and navigate through various terrains due to their compliance.\textsuperscript{[111]} Soft bioinspired 3D-printed locomotion robots were developed to be powered by pneumatic air pressure.
to navigate their environment by jumping,[42] crawling (Figure 5C),[45,72,93] undulating,[94b] hopping,[23a] and walking (Figure 5D).[23a,71b,78] Such soft robots can be modular,[93] and scalable[83a] besides their softness and ability to handle extreme conditions which make them highly customizable for various locomotion applications including lifting moderate and heavy loads for cargo transport applications.[80,87]

2.5.3. Artificial Muscles

Soft artificial muscles that can mimic the behavior of natural muscles are desired for various robotic systems and devices such as humanoid robots where they are required to move various joints (Figure 6).[23a,49] Soft 3D-printed pneumatic artificial muscles have several advantages including high power density,
high output force, fast response (Figure 5A), compliance, durability, modularity, accessibility, affordability (Figure 5B), and scalability. In addition, they either expand or contract in volume to generate the desired output displacement and desired force (Figure 5C, D). In addition, such artificial muscles can be used to lift heavy loads and generate various modes of deformation (Figure 5E).

2.5.4. Assistive, Medical, and Haptic Feedback Devices

Assistive and medical soft robotic devices such as wearable robots can be built using soft robotic concepts and actuated using soft 3D-printed pneumatic actuators for human performance augmentation and rehabilitation applications (Figure 6A). Soft, 3D-printed, and wearable upper limb exoskeletons and hands for finger, wrist, elbow and hand rehabilitation (Figure 6A, C) are built to help patients with the recovery of their functional motor skills and assistance in daily activities. Also, lower-limb wearable soft devices with haptic feedback capabilities based on pneumatics are developed to assist stroke patients and improve biofeedback provided during the rehabilitation process (Figure 6B). Moreover, soft wearable devices can augment human performance or assist in some tasks. Finally, soft robotic and prosthetic hands are developed as assistive devices based on 3D-printed pneumatic actuators to replace a lost upper limb and recover partially some of its functions.

3. 3D-Printable Soft Pneumatic Sensors

3.1. Working Principle

Soft pneumatic deformable structures (i.e., sensing chambers) can be designed and 3D printed using a range of soft materials to sense different input mechanical modalities, and therefore they can be implemented in soft robotic systems and devices as soft and functional sensors. These soft pneumatic sensing chambers rely on the volume change in their internal structures when they are mechanically deformed to operate and generate a useful output signal (Figure 7). Generally, such sensing chambers require additional air pressure sensors to translate the volume change into a pressure change following Boyle’s law that states that the pressure of a gas tends to increase as the volume of its container decreases at a constant temperature. This law can be written as $P_1V_1 = P_2V_2$ where $P_1$ and $V_1$ are the initial volume and pressure of a sensing chamber, respectively, and $P_2$ and
Figure 6. 3D-printed soft artificial muscles. A) A soft artificial muscle based on bending 3D-printed soft vacuum actuators activating an elbow joint. The muscle lifting a mass of 28.48 g by a height of 30 cm for 1.03 s when 90% vacuum is applied. B) Soft artificial muscles as biceps and triceps actuators powered at 20 W (20 V, 1 A) moving an elbow joint. Reproduced under the terms of the CC BY license. Copyright 2017, The Authors, published by Springer Nature. C) A 3D-printed miniature vacuum artificial muscle producing a linear motion by buckling under negative pressurization. Reproduced with permission. Copyright 2019, Wiley-VCH. D) A 3D-printed artificial muscle based on linear soft vacuum actuators lifting a load of 0.5 kg. Reproduced with permission. Copyright 2019, IEEE. E) A silicone-based 3D-printed soft artificial muscle lifting a load of 500 g. Reproduced under the terms of the CC BY license. Copyright 2018, The Authors, published by Springer Nature.

Figure 7. 3D-printed soft wearable rehabilitation and haptic feedback devices. A) A soft wearable glove for upper-limb rehabilitation applications helping a user to grasp an object. Reproduced with permission. Copyright 2018, Wiley-VCH. B) A soft haptic device for lower-limb rehabilitation applications. Reproduced with permission. Copyright 2019, IEEE. C) A soft wearable rehabilitation glove for post-stroke finger spasticity evaluation. Reproduced under the terms of the CC BY license. Copyright 2020, the Authors, Frontiers Media SA.
V₂ are the final pressure and volume of a sensing chamber, respectively, when it is mechanically deformed (Figure 8). This relationship between the volume and pressure for sensing chambers suggests that when a sensing chamber expands its internal pressure decreases and when it contracts, its internal pressure increases. This change in pressure can be directly measured using a pressure transducer and therefore various structures can be designed and built to develop interactive and sensitive soft robotic devices.

3.2. Materials and Fabrication

The advancements in additive manufacturing technologies made it possible to fabricate responsive airtight soft pneumatic sensing chambers with various topologies. Low-cost and open-source FDM 3D printers that use a commercially available thermoplastic poly(urethane) (TPU) were used to fabricate soft pneumatic sensing chambers rapidly and directly without requiring support materials and postprocessing. Also, commercial PolyJet printers that can print multiple materials with different properties were used to fabricate rigid components as well as soft pneumatic touch sensing skins and soft robotic skins made of a commercially soft material known as TangoPlus that exhibits a rubber-like behavior. Also, SLA 3D printing was used to fabricate pneumatic touch buttons using an elastic commercial resin.

3.3. Sensing Capabilities and Modalities

The pneumatic sensing chambers can sense different input mechanical modalities of compression, bending, torsion, and rectilinear displacement. FEM can be used to design and optimize soft pneumatic sensing chambers to generate a linear response between their input and the corresponding output. Also, such chambers can be used as touch, single and bidirectional bending, linear and torsional sensors, and in some cases, such modalities can be achieved using the same sensing structure based on their topology and their behavior upon deforming.

3.4. Applications

Soft pneumatic sensing chambers can be used in diverse robotic systems and devices including soft wearable robots, humanoid robots, human–machine interfaces, interactive devices and robots, haptic feedback devices, game controllers, and robotic and prosthetic hands. Touch (i.e., force) sensors directly used to achieve real-time force control in soft robotic fingers safely interact with soft robotic skins for applications involving human–robot interaction. Linear soft sensors can be used in hybrid game controllers made of soft and rigid materials. Finally, torsional soft sensors can be used to develop hybrid throttle controllers and interactive robotic skins.

These examples prove that soft 3D-printable soft pneumatic sensing chambers can be used in a wide range of soft robotic applications for various purposes where they can be tailored using geometric modeling and 3D printing to target specific requirements. In addition, they can be extended to be used reliably for closed-loop feedback control in different robotic systems including haptic feedback systems and soft robotic fingers and grippers.

3.5. Advantages and Limitations

The developed soft pneumatic sensing chambers have several advantages compared with existing soft sensors. First, such sensors can be rapidly modeled and designed to be fabricated using various 3D-printing technologies. Therefore, they are highly customizable. Second, such sensors can be used to sense different mechanical modalities either separately or simultaneously. Third, such sensors can be designed to have several characteristics such as fast response, linear response, insignificant hysteresis, repeatability, reliability, stability, durability, and very low power consumption. Fourth, they can be 3D printed simultaneously in the same soft monolithic structure along with soft actuators. These characteristics are often not present in other soft sensors based on different technologies and therefore limit their usability, especially in control applications of soft robotic systems. Finally, they can be directly used in various applications including soft interactive robots and human–machine interfaces for communication or interaction between, for example, a physically assistive device and its user. The human–machine interfaces based on such chambers can be placed on users to identify their intentions and physiological
conditions and consequently generate necessary cues or signals to control and guide a robotic device or regularly update on the progress of their recovery, if it is used for rehabilitation purposes.

Despite all these advantages, these deformable pneumatic sensors have few drawbacks. First, they are not by themselves soft sensors. These soft chambers require solid air pressure sensors to measure the change in their internal volume (i.e., pressure) and consequently, they are not completely soft. Second, as their operation requires a change in their internal volume and solid air pressure transducers, it is challenging to miniaturize them. Finally, their structural stiffness might limit their integration in certain applications as they are not made of stretchable silicone-like materials.

4. Discussion
4.1. Challenges of Soft Pneumatic Robots and Devices

As soft pneumatic actuators continue to be the most used actuators, they still face some challenges in terms of their integration and usage in soft robotic devices for a specific function and application.

4.1.1. Portability

Soft pneumatic actuators require additional equipment such as a pressure source to operate that in turn requires power supplies, complex electric circuits, and various components such as valves to operate. This additional pneumatic equipment is usually bulky. This requirement hinders the adoption of such systems for developing portable soft robotic devices and limits their usability in applications where weight plays a significant role such as in soft prosthetic hands as the mobility of the user is significantly affected. However, they are suitable for other applications such as soft wearable exoskeletons or rehabilitation devices that can be used at home or in a healthcare facility. Also, one might argue that such actuators can be significantly miniaturized using 3D printing technologies and therefore their additional equipment can be dramatically downsized. While this is possible and achievable as demonstrated in Figure 9.

Figure 9. 3D-printed soft human–machine interfaces. A) Wearable soft gloves, soft human–machine interfaces, and haptic feedback devices based on soft pneumatic sensing chambers. Reproduced under the terms of the CC BY license. Copyright 2019, Wiley-VCH. B) A soft robot with an interactive soft and deformable skin. Reproduced with permission. Copyright 2012, IEEE. C) A soft pneumatic airtight robotic skin for contact sensing and gentle grasping. Reproduced with permission. Copyright 2015, IEEE. D) 3D-printable interactive soft and hybrid pneumatic devices. Reproduced with permission. Copyright 2013, the Authors, ACM, Inc. E) 3D-printable soft and hybrid pneumatic devices for game controllers and haptic feedback devices. Reproduced under the terms of the CC BY license. Copyright 2018, the Authors, EDP Sciences.
the literature and desired for haptic feedback applications,\textsuperscript{[128]} for instance, where a small mechanical output (i.e., force) is needed, it has some unfavorable effects on the output force that the actuators can generate. Therefore, there is a tradeoff between the overall size of the device and its function or application.

4.1.2. Noise and Vibration

As soft pneumatic actuators are driven by air compressors or vacuum pumps,\textsuperscript{[129]} they generate some levels of noise and vibrations that are usually not desired. Although some techniques and tools can be used to reduce the noise and vibration levels, these stand as limitations when it comes to portability as additional components are added to the system.

4.2. Requirements for Soft Actuators

Here we present a list of what is suggested or required to develop functional soft actuators. The soft actuators should have one or more of the following characteristics depending on the application and requirements.

- Soft, flexible, and stretchable, responsive, or active, with programmable properties. For instance, their tangent modulus should range between 100 and 1000 MPa and should be able to exhibit strains between 10% and 100\%\textsuperscript{[4,130]} The tangent modulus is obtained by considering the slope of the stress–strain plot at a certain point just beyond the elastic region where the relationship between the stress and strain is nonlinear. The tangent modulus is for materials deformed beyond their elastic limits. Hydrogels, silicones, polyurethanes, and electroactive polymers are typical soft synthetic materials that have a tangent modulus within these specified ranges. This range for the tangent modulus is consistent with the mechanical properties of biological materials ranging from body fat to tendon.\textsuperscript{[4]}

It is desirable that the compliance of a soft robot should be below the compliance of its environment as it is assumed that the robot will or might directly interact with humans and other similar delicate environments. Also, as the materials for soft robots are viscoelastic, the storage modulus of the actuator materials should be used in decision-making and comparison. The storage modulus is obtained in the frequency domain where sinusoidal loads or stresses are applied, rather than its tangent modulus to decide on the actuator material as the tangent modulus is obtained under static or quasistatic loading conditions. To this aim, 1000 MPa can be taken as the ultimate limit of the storage modulus for soft synthetic materials for soft robotic systems and their actuators.

- Low cost (i.e., affordable), amenable to additive manufacturing technologies where it can be easily scaled and if possible, no molding and postprocessing should be required.
- Programmable mechanical (e.g., variable stiffness and damping constants), rheological (e.g., variable viscoelastic moduli, stress relaxation modulus, and shear viscosity) and electrical properties (e.g., resistance, capacitance), and parameters.
- Durable, reliable, and resistant to fatigue under large and reversible strains.
- Biocompatible where no toxic or harmful products are used.
- Integrative and distributive like natural muscles that smoothly contain the structure, support, and actuation, and where 30–80\% of their fibers contribute to the generation of the force output.
- A high percentage of actuator mass should contribute to the force generation. A high active/total mass ratio of up to 80\% will be ideal.
- Allow developing an effective actuation concept compatible with a sensing concept, flexible and stretchable electronics, and power source which can be seamlessly integrated into a continuum body with an overall low footprint.
- Reversible and predictable behavior with a reasonably short response time of less than 1 s.
- A linear response with high sensitivity and negligibly small hysteresis and creep.
- Low cost to increase its accessibility and low power.
- High durability and robustness to disturbances.

4.3. Requirements for Soft Sensors

Similarly, we present a list of what is suggested or required to develop functional soft sensors. Soft strain sensors should have one or more of the following characteristics depending on the application and requirements:\textsuperscript{[131]}

- High stretchability or mechanically compliant to the compliance of the surface it will be placed on. For example, an electronic skin or artificial skin should be stretchable up to 75\% strain. For comparison, the stretchability of the knee skin is on the order of 55\% strain.\textsuperscript{[131b]}
- Made of materials with a modulus of elasticity ranging between 25 and 1 MPa and ultimate strain >200\%.\textsuperscript{[53,131b]} For comparison, the human skin has a modulus of elasticity that ranges between 25 and 220 kPa.\textsuperscript{[53]}
- Ability to measure a range of complex sensations such as shear, lateral deformation, and vibration.
- Durable, reliable, and resistant to fatigue under large and reversible strains and biocompatible where no toxic products are used.
- Low cost (i.e., affordable), amenable to additive manufacturing technologies where it can be easily scaled, and if possible, no molding and postprocessing should be required.
- Low footprint: packaging a strain sensor with its power source, signal processing, recording, communication, and data storage units.
- Reversible and predictable behavior with a reasonably short response time of less than 1 s.
- A linear response with high sensitivity and negligibly small hysteresis and creep (i.e., no change in the sensor’s reading with time, temperature, humidity, and other environmental conditions).

4.4. Future Outlooks

The soft robotics field is changing the way we think, build, interact, and most importantly perceive robots. Robots have long been perceived as machines made of metals that their sole purpose is to perform repetitive tasks in isolated environments. However, with the development of soft robots, this view is dramatically changing and will almost vanish in the future where robots will
start to look and behave eventually like humans, animals, and plants as they take inspiration from nature. The continuing advancements in additive manufacturing technologies and soft smart materials will allow us to 3D print entirely soft robots that can walk out of the printers with all the required elements such as actuators, sensors, electronics, and power sources. Also, the development of soft intelligent robots will expand vastly as the tools needed to build them are advancing very rapidly and becoming more affordable, accessible, and readily available for the community.

Also, similar to conventional robotic systems, when establishing a soft robot or a soft robotic system, a designer should make a balanced decision about many parameters such as weight, overall size, cost, operation life, dexterity, robustness, and control difficulty. This subsequently determines the optimal number and placement of the actuators, sensors, motion transmission elements, mechanical compliance, power source, controller, and the materials to be fabricated from and the fabrication technology to be used. The fundamental question is how to place actuators and sensors such that they require minimum control effort and energy without trading off the safety and performance of the robotic device. The energy consumed and space required by the sensors should be much smaller than those of the actuators. This follows that some intelligence should be embedded in the robotic system right at the start of the design stage such that the robotic system can meet all these specifications and safely interact and adapt to its immediate environment. The latter is especially crucial for soft robotic systems to support their rationality for applications involving smooth touches, safe interaction with humans (e.g., assistive and rehabilitation devices), manipulating and handling delicate objects, yields, and agricultural products, which are not ideally suited for conventional robotic systems.

Finally, progress in smart soft materials amenable to additive manufacturing synergistically combined with existing science and engineering knowledge and know-how in mechatronic systems, especially in the general area of robotics, are essential to realizing soft robotic systems. This synergy requires making crucial decisions and choices right at the start of the design and reflecting them on the material selection and manufacturing of the soft robotic system, which will efficiently meet the design, user, function, and application requirements. It must be emphasized that the user-centered design requirements including ethics should be satisfied by the robotic devices (i.e., typified by physically assistive devices and rehabilitation devices) where humans are in the loop, for which the progress in soft robotics is crucial. Not only technical requirements but also user-centered requirements including ethics, also known as the ethics-based co-design approach, should equally be implemented in the design and development of robotic systems, including their actuators and sensors, to minimize end-user risk and close the loop around the establishment of function, application and user-specific soft robotic systems.\[1,12]\]

We expect this Review to stimulate more interaction between materials scientists and robotic researchers to synthesize soft and functional materials that can meet application, function, and user requirements, in a way to implement the top-down approach to shorten the path between science and the application of soft smart materials and their use in establishing functional soft robotic systems.

5. Conclusion
This Article has presented a comprehensive review of soft pneumatic actuators and sensors that can be fabricated using various additive manufacturing technologies. The types of such soft pneumatic actuators including positive-pressure and vacuum actuators are presented in terms of their advantages, limitations, materials, functions, capabilities, and applications. Similarly, soft pneumatic sensing chambers that can be used as soft sensors in diverse robotic applications are presented and discussed in terms of their working principle, materials, fabrication, sensing capabilities, applications, advantages, and limitations compared with existing soft sensing technologies. Also, this article has discussed the challenges facing soft pneumatic actuators and sensors and provided a list of what is needed and suggested for developing functional soft actuators and sensors that can be embedded in diverse robotic applications.

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Conflict of Interest
The authors declare no conflict of interest.

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