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Review

Pneumatics in Service Robotics: A Review Across Application Domains and the Impact of Soft Robotics

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Abstract

Soft robotics is a rapidly evolving field that has attracted significant attention within the scientific community. This review analyzes the main advantages of pneumatic technology in service robots across the different application domains defined by the International Federation of Robotics (IFR). By organizing the literature according to application domains, this work aims to clarify the specific benefits of pneumatic and soft pneumatic solutions in each context. The proposed approach distinguishes between traditional pneumatic solutions and the subsequent emergence of soft robotics, in order to highlight how and to what extent soft technologies have reshaped the design and application scenarios. Particular attention is devoted to the role of materials and recent manufacturing techniques used by researchers to fabricate soft pneumatic robots. Based on 163 selected papers, the analysis reveals that medical and agricultural applications dominate soft pneumatic research, accounting for 41% and 27% of the soft sample, respectively. Compared to traditional pneumatics, the medical sector has expanded into cardiac assistive devices, wearable monitoring sensors, and minimally invasive surgery; agriculture has grown from 17% to 27% of the soft literature due to precision harvesting grippers. Soft inspection robots have increased thanks to continuum manipulators and bio-inspired locomotion, while search and rescue remains a niche (9%) but promising sector. Unlike previous reviews that focus on single domains or technologies, this work quantifies the uneven transition from rigid to soft pneumatics across IFR sectors and highlights emerging application-specific design paradigms that were not feasible with traditional systems.

Keywords: service robotics; soft robotics; soft actuators; pneumatics

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1. Introduction

Robotics was initially developed to replace human beings in industrial tasks and to meet the flexibility demands of modern production plants. Since then, the results achieved and the technological solutions developed in this multidisciplinary field have influenced the scientific community in creating technologies more directly focused on human needs. This trend in robotics is known as service robotics, for it prioritizes societal needs and requires strong interaction between humans and robots [1]. By its very nature, service robotics provides multiple areas of study for researchers. A service robot must be capable of operating in an environment that is not predetermined (unstructured or semi-structured environment), while also understanding human behavior, cooperating with people, and, above all, ensuring that it does not harm or injure them [2].

It is clear that these fundamental requirements generate multiple research topics, which aim to address, either individually or collectively, the related challenges. Among these topics, there is the development of compliant systems for grasping and manipulating fragile objects, whose geometry and properties are not known in advance [2], as well as the development of safe and lightweight systems for human collaboration [3–7].

Pneumatic systems have traditionally been one of the possible solutions for controlling those devices. They consist of actuators, sensors, switches, logic elements, interface components, directional valves, proportional valves, storage systems, and air treatment units. At an industrial level, these elements are managed through programmable logic controllers (PLCs) and work together to regulate production processes. In the field of service robotics, initially, there was essentially a transposition of pneumatic technologies previously developed for the industrial sector [8,9].

Conversely, when referring to soft robotics and how they changed this approach, the most commonly cited example is that of the McKibben muscle, a unidirectional pneumatic actuator whose invention is attributed to Richard H. Gaylord (1958) [10], but was taken up a few years later by the American atomic physicist Joseph L. McKibben in order to create an exoskeleton to assist the weak musculature of the upper limb of people affected by poliomyelitis [11,12]. The McKibben muscle represents the precursor, and still remains one of the remarkable examples of soft robotics. Over the past two decades, it has been the subject of various studies aimed at its modeling [13–15], its realization using innovative techniques [16–18], and its use in Service Robotic Systems [19–22]. However, in essence, it is a pneumatic actuator made using soft materials, namely an inner tube (bladder) and an outer sleeve to constrain and impose the muscle deformation. Unlike a traditional single-acting pneumatic cylinder, the McKibben muscle generally behaves like a linear actuator, but a force perpendicular to its axis can cause it to bend. For this reason, and due to its rubber (or similar) walls, the McKibben muscle is considered a soft actuator and can therefore interact with humans and natural environments with greater safety.

As mentioned, the McKibben muscle represents only the first example of a series of scientific activities that, since the early 2000s, have given rise to the new technological field of soft robotics. A 2024 study conducted by Aracri et al. [23] highlights how, in the early years of the millennium, soft robotics experienced steady but modest growth, with 500 articles published in 2015. From 2016 onwards, however, the development was of an entirely different nature, with 2500 articles published in 2021 alone. The fundamental principle behind all the work is essentially the same: the development of robotic systems based on deformable materials, mainly made of soft and compliant materials [24]. Figure 1 provides a schematic overview of the main drivers behind the adoption of pneumatic systems in service robotics, along with the key added values introduced by the recent developments in soft robotics.

The scientific literature includes several reviews that analyze the world of soft robotics. The review by Kim et al. [25] presents various types of bio-inspired soft robots. The more recent work by Alici and Tawk [24] analyzes soft actuators and sensors fabricated using additive manufacturing, while the 2018 work by Shintake et al. [26] focuses on soft robotic grippers. Finally, the 2017 work by Polygerinos et al. [27] specifically addresses pneumatic soft robotic technologies. Other reviews focus on specific application domains, such as soft mobile robots [28], soft actuators [29], and soft robotics for agriculture [30].

Despite these contributions, there is still a lack of a systematic mapping of soft pneumatic robotic systems within the context of service robotics, particularly with respect to how their advantages emerge across different application domains. This paper presents a narrative review aimed at systematically organizing pneumatic robotic technologies across the main service robotics application domains identified by the IFR [31]. The analysis highlights the evolution from traditional pneumatic solutions to soft robotic approaches, emphasizing how this transition has reshaped application scenarios and design paradigms.

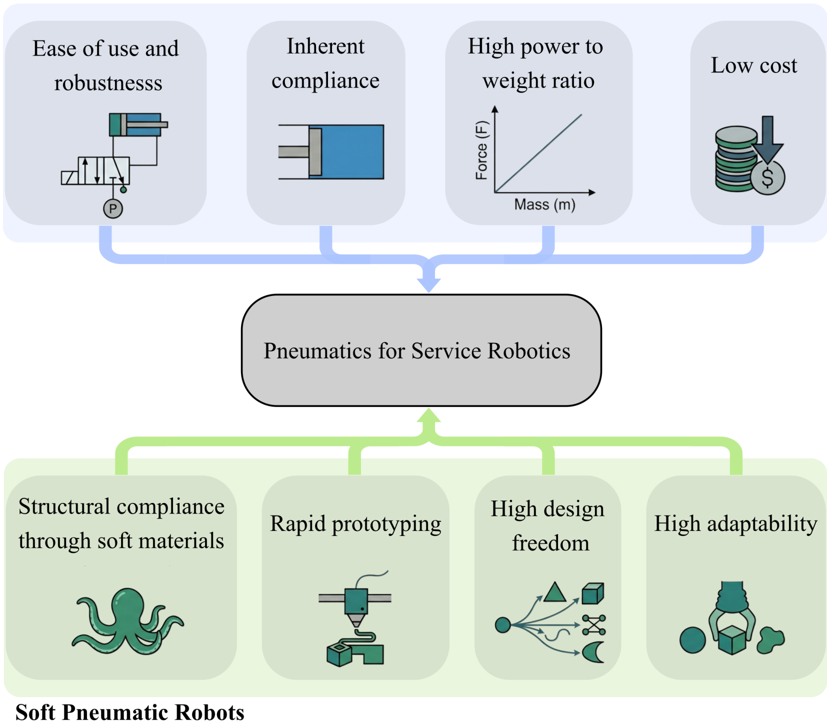

Figure 1. Key enabling factors of pneumatic technology for service robotics applications.

The remainder of this paper is organized as follows. Section 2 summarizes the review methodology. Section 3 describes traditional pneumatic solutions across the IFR application domains. Section 4 focuses on soft robotic approaches. Section 5 discusses the role of materials and manufacturing methodologies in the development of soft pneumatic robots. Section 6 addresses current limitations and future perspectives. Finally, Section 7 concludes the review.

2. Review Methodology

The literature considered in this review was collected from the Scopus and Google Scholar databases. Two distinct time windows were defined in order to capture the evolution from traditional pneumatic systems to soft pneumatic robotics.

For traditional pneumatic systems, the analysis was restricted to the period between 1995 and 2018. Search queries included combinations of keywords such as "pneumatic robot", "pneumatic exoskeleton", "pneumatic gripper", and "pneumatic mobile robot", combined with specific application domains (e.g., "pneumatic gripper for agriculture" or "pneumatic mobile robot for inspection").

For soft pneumatic robots, the time window spans from 2015 to 2026. The search strategy included terms such as "soft pneumatic robot", "soft pneumatic gripper", "soft pneumatic wearable", and "soft pneumatic mobile robot", as well as morphology-related keywords such as "legged robot", "snake robot", and "worm robot", combined with the corresponding application domains.

For Section 5, the research also included keywords such as "soft pneumatic actuator" and "soft pneumatic robot", in order to capture relevant works not categorized by the authors into a specific application domain.

After removing duplicates and screening titles and abstracts, 163 unique papers were considered for discussion. Among these, 51 focus on traditional pneumatic systems (1995–2018), 75 on soft pneumatic robots (2015–2026), and 37 on materials and manufacturing methods. Exclusion criteria were (i) application domain not clearly related to IFR service robotics, (ii) papers lacking a physical prototype, and (iii) non-English publications.

3. Pneumatics for Service Robotics

As mentioned, the use of pneumatic devices in service robotics contexts originated as a natural extension of the advantages of industrial pneumatic systems. Pneumatic systems are intrinsically compliant, as the compressibility of air allows for the absorption of unwanted forces, and they are also characterized by a high force-to-weight ratio. An additional advantage is their high reliability, since they rely on relatively simple physical principles. Figure 2 illustrates the application of traditional pneumatic systems across the various sectors identified by the IFR. Robots are classified into three main categories: exoskeletons and wearables, manipulators, and mobile robots. The remainder of this section provides a detailed overview of the solutions proposed across the different application domains.

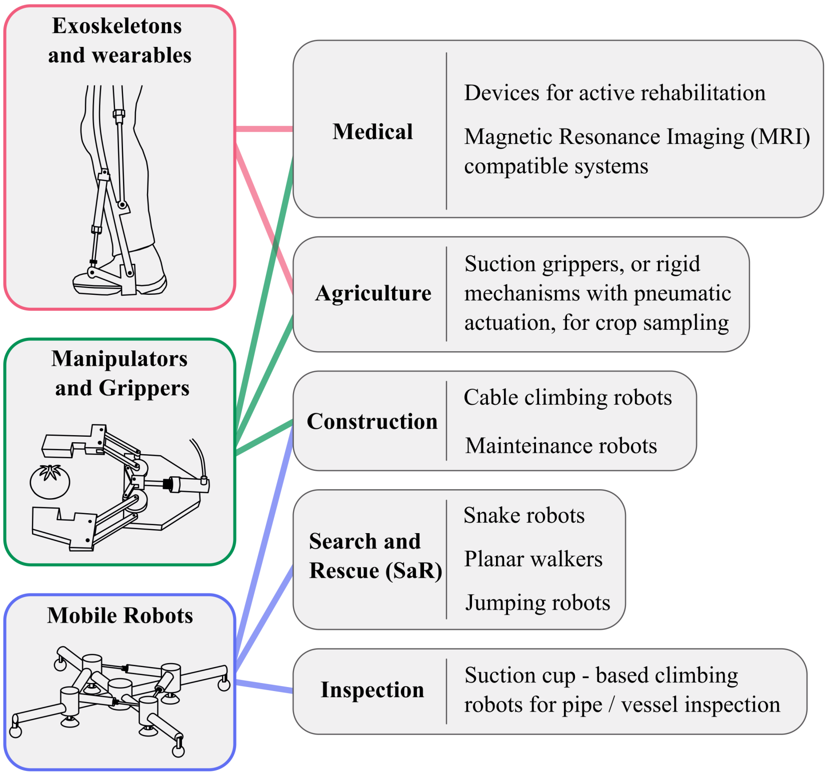

Figure 2. Traditional pneumatic systems in the application macro-areas of service robotics according to IFR (professional application and medical) [31].

3.1. Pneumatic Robots for Medical Applications

Among the various actuation technologies, pneumatic devices for medical applications are among the most widely used. The primary need was to create systems that were safer for humans. Within this scenario, the study by Morales et al. [9] discussed the use of pneumatic technology for the development of robotic rehabilitation systems. The reason behind the development of rehabilitation robots directly originates from well-established findings in medical science, which demonstrate how physical exercises based on voluntary movements can produce significant clinical results in motor recovery. Physical exercise based on voluntary movements enables both functional recovery following damage to the central nervous system [32] and neurogenesis, i.e., the formation of new neural connections [33].

A robotic system can thus help structure a rehabilitation procedure that is repetitive, monitored, and reduces the workload on therapists [34–36].

Most of the proposed solutions in this field consist of rigid mechanical structures arranged in parallel with the user's kinematic chain, actuated by pneumatic cylinders for the advantages discussed above. For post-stroke upper limb rehabilitation, for example, Jackson et al. [37] developed the intelligent Pneumatic Arm Movement (iPAM), a dual-arm robot with upper and lower orthoses for each arm that does not require adjustment for the user's limb dimensions. Similar architectures can be found in the Robotic-assisted Upper-extremity Repetitive Therapy (RUPERT) device [38], the Pneu-WREX [39], and the work by Morales et al. [40] and others examples [41,42]. Pneumatic robotic systems have also been developed specifically for wrist rehabilitation, such as the Hand-Wrist Assisting Robotic Device (HWARD) [43] and similar systems [44,45], with a variable number of degrees of freedom depending on the desired exercise type.

A significant portion of the literature has focused specifically on finger rehabilitation, where the precision and compactness of pneumatic cylinders are particularly advantageous. Ma et al. [46] developed a modular exoskeleton manipulator actuated by a mini pneumatic cylinder. Heo and Kim [47] proposed the Open Fingerpad Exoskeleton (OFX), which preserves tactile sensation while providing assistive force via a pneumatic cylinder. Patar et al. [48] presented PAFEx, a low-cost device for thumb and index finger rehabilitation. The Festo ExoHand is an industrial solution originally developed for teleoperation but also explored for rehabilitation. The mechanical structure is customized to the user's anthropometric measurements, and actively controls the flexion and extension of each individual finger [49].

For the lower limb, examples include the 6-d.o.f. Pneumatic Interactive Gait Rehabilitation Orthosis (PIGRO) [50] for gait training and the work by Aoyagi et al. [51] to assist pelvic motion during walking.

A second type of application in the medical field concerns the development of devices compatible with magnetic resonance imaging (MRI) [52,53]. There are indeed some procedures, such as needle insertion [54,55], biopsy interventions [56,57], and catheter placement [58,59], that require imaging modalities to provide multi-parameter imaging to the medical staff. The use of robotic systems in this field reduces the time required for the procedure and improves needle placement accuracy. However, it is clear that the use of electric motors is not possible, as they would compromise the MRI outcomes and vice versa. Pneumatic actuation, then, becomes one of the feasible technological solutions. In this case, the use of dielectric materials for the pneumatic components ensures the complete absence of electromagnetic interference, but the compressibility of air represents a disadvantage, as it introduces time delays and back-drivability [60]. A final class of MRI-compatible applications concerns brain imaging: pneumatic robots move the patient's limbs or fingers to observe the reaction of the damaged brain [61,62].

3.2. Pneumatic Robots for Agriculture

Agricultural robotics represents another sector in which pneumatic technology exploits its inherent compliance for crop sampling or harvesting. The main design requirement, therefore, consists of handling delicate objects with complex and variable shapes, whose rough or highly curved surfaces require an adaptable and compliant system. The work of Foglia and Reina [63], for example, presents a double four-bar manipulator and a two-finger rigid gripper, whose actuation is achieved solely through pneumatic actuators (cylinders for the manipulator, pneumatic muscle for the gripper). In this case, the requirement for adaptability to different shapes is not met, as the solution is specifically developed for harvesting a particular variety of radicchio. There are also similar works on grippers or rigid manipulators actuated by pneumatic actuators [64–66]. The geometric variability, as well as the fragility of objects such as strawberries, eggplants, peppers, etc., has also led to the development of suction grippers, such as the gripper for eggplant firmness evaluation by Blanes et al. [67], the cherry peduncle detacher by Tanigaki et al. [68], or the sucker-cutter gripper for sweet pepper harvesting by Lehnert et al. [69].

Only a few exoskeletal systems have been proposed to assist farmers in high-load tasks, such as the work by Yagi et al. for support the shoulder and elbow movement [70]. Their number remains very limited and they are mostly adapted from traditional industrial scenarios.

3.3. Pneumatic Robots for Inspection and Surveillance

In the case of inspection activities, the use of pneumatic robots is mostly exploited for the development of locomotion robots. The main advantage here is their safety and the ability to navigate in particularly hostile environments. The Nuclear Electric Robot Operator (NERO) [71], for instance, is a climbing robot for the inspection of nuclear reactor pressure vessels. Pneumatic technology is used to create the motor structure, with vacuum grippers as feet and pneumatic cylinders as legs. The robot is intrinsically safe since, in the event of an electrical failure in the control system, the valve system automatically brings the robot to a safe condition. Given the low cost, simple control, and high adhesion forces, suction cups have, in fact, been among the most used solutions for the creation of inspection climbing robots [72,73]. The ROBICEN family of devices, for instance, was designed for pipe and tank inspection in nuclear power plants using vacuum suction cups [74]. Similarly, White et al. exploited a similar approach for a climbing robot for the aerospace industry [75].

Another common design for inspection tasks takes inspiration from biological locomotion. Snake-like robots, such as the SSR-II, use pneumatic bellows to move in narrow spaces like pipelines [76]. For pipe inspection, a variety of inchworm and earthworm-inspired robots have been developed, among which the solution by Yoon and Park represents a valid example [77]. Others include a micro robot capable of moving in a 10 mm pipe using a single pneumatic line [78] and a three-somite earthworm robot that can navigate long pipes [79].

3.4. Pneumatic Robots for Search and Rescue

Regarding search and rescue applications, pneumatics have been exploited in a similar fashion to what proposed for inspection scenarios. For example, an architecture similar to that of Yoon and Park [77] was used by Chen and Yeo [80] to build a search and rescue robot that exploits the inchworm motion concept. The planar walker combines a series of pneumatic actuators and suction grippers to create a reconfigurable quadrilateral structure that allows for the generation of a two-dimensional gait. The suction grippers represent the potential anchor points to the ground, and the pneumatic cylinders form the links of the quadrilateral; their actuation causes the reconfiguration of the structure. In the same application theme of search and rescue robotics, pneumatic actuators have been used for the actuation of active joints between modules of the OmniTread snake robot [81]. The work of Ohno and Hirose [82] shows, instead, a remarkable example of a system where the basic unit, called the SR unit, is an active pneumatic unit with three degrees of freedom and integrated control (valves, sensors, controller). The SR unit is provided with three pneumatic actuators arranged in parallel configuration, and it has a cylindrical encumbrance with a diameter of 120 mm, and a longitudinal stroke of 63 mm (from 114 to 177 mm). A series of SR units are eventually implemented to create a snake robot with a winding gait. A final application context of pneumatics in service robotics involves providing the mechanical power needed to perform a jump. Tsukagoshi et al. [83]

developed a search and rescue robot weighing 2.3 kg, equipped with differential steering wheels, and an additional jumping mechanism realized using a pneumatic actuator. The switching of a 3-way 2-position spool valve connects to a pressurized air reservoir (0.7 MPa), which enables the robot to jump to heights of 80 cm, or 3.5 times the height of the robot.

3.5. Pneumatic Robots for Construction

Although the construction robotics sector is niche, examples of pneumatic solutions in this field include the development of cable-climbing robots for cable-stayed bridge maintenance [84,85] and robotic manipulators for window glass mounting [86].

4. The Advent of Soft Robotics

While traditional pneumatics found its application by adapting developments from the industrial sector to the context of service robotics, soft robotics operates at a generally deeper level, starting from the redesign or, in many cases, the complete reinvention of the fundamental components of a pneumatic system [27].

The distinction adopted in this review is as follows. Traditional pneumatic systems rely on rigid actuators to drive multi-joint mechanical structures, whereas soft pneumatic systems employ actuators, sensors, and in some cases circuitry made of deformable materials.

This increase in design space is enabled by recent advances in additive manufacturing and by innovative soft actuator fabrication techniques, which allow researchers to pursue complex and often bio-inspired shapes. This aspect plays a key role in recent developments of soft robotics, and for this reason the following section will discuss it in more detail.

Examples of the remarkable creativity of researchers include numerous single-motion or multimotion pneumatic actuators and the development of small and flexible suction cups [87], as well as the development of pneumatic components such as directional or oscillating valves [88,89].

In line with the objectives of this work, this section will delve into studies from the scientific literature that present an explicit and strong reference to one or more IFR application contexts and where soft pneumatic robotic systems have provided an additional contribution compared to what was discussed in Section 3. A summary of this analysis is provided in Figure 3. The macro-application contexts remain essentially the same, with the sole disappearance of construction robots, but it is evident that many sub-fields have changed significantly, indicating that soft robots are now designed to respond to different needs.

4.1. Pneumatic Soft Robots for Medical Applications

Regarding medical soft robots, it is evident that the field of rehabilitative devices can only benefit from the introduction of soft structures [90]. There are also additional contexts, such as systems for minimally invasive surgery and cardiac devices, where soft pneumatic systems find their utility. A comprehensive review, dated 2019, was conducted in [91] and is revisited here with more recent developments.

Concerning rehabilitative systems, the main advantages of employing soft systems consist of mechanical compliance, which is already a characteristic of traditional pneumatic systems, but is further enhanced by the use of soft materials, and low weight. Figure 4 displays some examples of medical soft pneumatic devices recently proposed in the scientific literature.

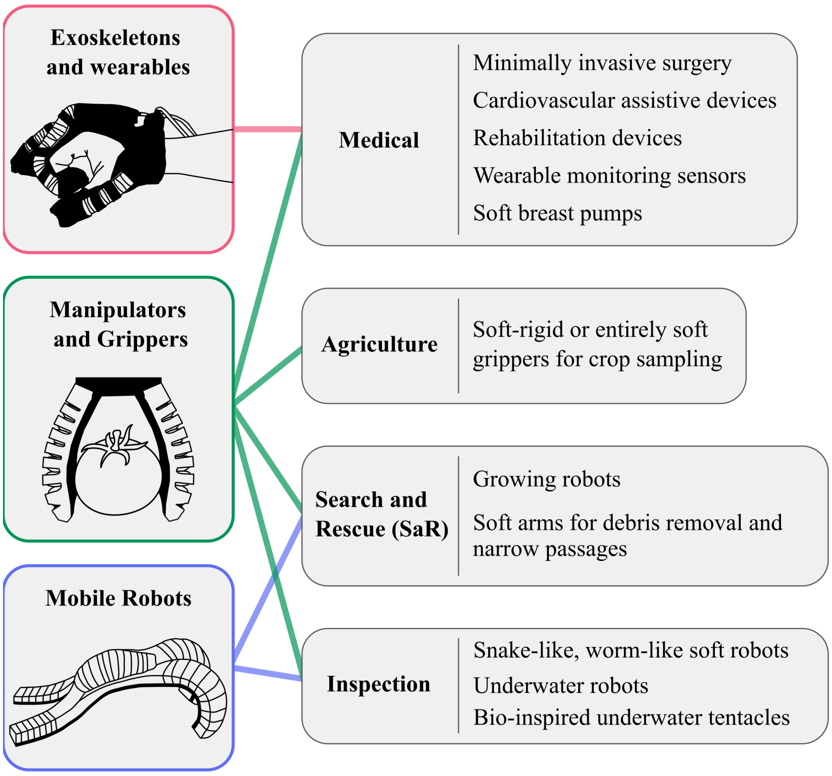

Figure 3. Soft pneumatic systems in the application macro-areas of service robotics according to IFR (professional application and medical).

A very popular trend regards wearable devices for wrist [92–94], finger [95–97], elbow [98–101], and ankle [102–104] rehabilitation, based on linear or bending soft pneumatic actuators of various types.

A smaller number of studies focus on the knee [105,106] and shoulder [107,108], likely due to the larger size of the actuators required, resulting from the greater range of motion and higher force demand. A notable example in this field is provided by the work of O'Neill et al. [108], where the authors proposed a bellow-like textile actuator to support shoulder adduction and horizontal flexo-extension for people with neuromuscular conditions.

A completely new and cutting-edge application context concerns the development of assistive cardiac devices [109]. In this regard, the research directions include either the complete reproduction of the organ through a so-called soft robotic total artificial hybrid heart [110], or through a soft robotic sleeve that wraps around the heart and uses pneumatic artificial muscles to provide direct cardiac compression, effectively acting as a ventricular assist device (VAD) without contacting blood [111,112].

Another innovative field compared to traditional pneumatics concerns minimally invasive surgery, which refers to surgical procedures where the surgical target is accessed through small entrances (laparoscopy, thoracoscopy) or natural orifices (endoscopy). The advantage of minimally invasive surgery lies, evidently, in the reduced impact on the patient, which has recently made it a major focus of research for the development of robotic devices. The operations generally required during surgery include grasping, divarication, dissection of the surgical target (e.g., an organ), and video recording to guide medical staff [113]. These can be performed using a single unit, in which case it is referred to as single-port minimally invasive surgery, or using multiple instruments, each inserted through an appropriate incision in the patient's body. For example, Kortman et al. [87] presented a suction gripper that, being foldable, can be inserted into the patient's body through a trocar. Further examples include the inflatable cable-driven robot by Yang et al. [114] and the bio-inspired soft manipulator with variable stiffness by Ranzani et al. [113].

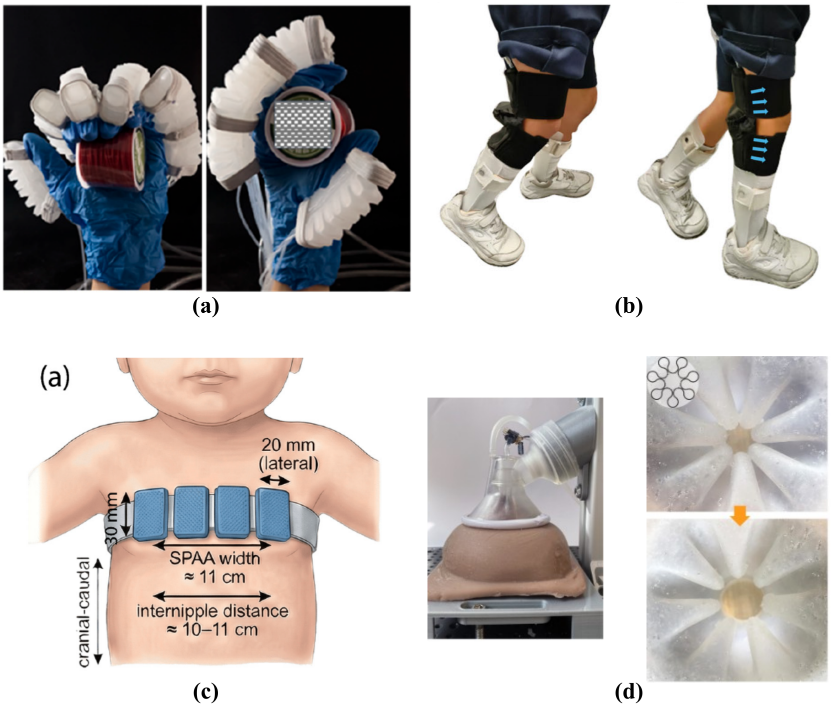

Figure 4. (**a**) Soft pneumatic wearable glove for hand rehabilitation. Adapted from [97] (CC BY 4.0). (**b**) Soft pneumatic exosuit for pediatric lower limb rehabilitation, adapted from [115] (CC BY 4.0). (**c**) Pneumatic Actuator array for torso stimulation in preterm infants. Adapted from [116] (CC BY 4.0). (**d**) The soft pneumatic breast pump proposed by the authors in [117].

An additional application regards compression therapy, where soft robotics aims to transform treatment strategies for conditions such as venous disease and lymphedema [118]. Intermittent pneumatic compression has been shown to be effective in improving the healing of venous ulcers, reducing wound closure times and alleviating pain, as demonstrated by clinical studies. The use of pressurization to apply controlled compression forces to the body is also exploited for other purposes, such as breast pumps to increase the breastfeeding mother's comfort during device usage [117,119] or pneumatic belts for intermittent colonic exoperistalsis [120].

4.2. Pneumatic Soft Robotics for Agriculture

The ability to manipulate delicate and geometrically-complex objects opens numerous application contexts for Precision Agriculture (PA) [30,121]. The topic has been extensively covered in the review by Shintake et al. [26], which deals with soft robotic grippers in general, while the reviews by Liu [30] (2023) and Zhang [122] (2025) specifically focus on food handling with several pneumatically actuated examples. Figure 5 shows a few examples of soft pneumatic grippers developed for PA purposes.

In this regard, the most employed motion principles for soft pneumatic actuators (SPAs) in grippers are bending and volumetric expansion, while linear and twisting SPAs are less common. Bending actuators are widely adopted due to their large range of motion and adaptability in grasping curved or complex-shaped objects. Many solutions are based on the PneuNet architecture, such as the gecko-inspired gripper proposed by Clark et al. [123], combining bending actuation with electrostatic attraction and suction. Another recent example is the three-finger bending gripper developed by Hou [124], based on a TPU (thermoplastic polyurethane) bladder and textile sleeve to tailor deformation behavior.

Tentacle-like soft pneumatic actuators, which achieve three-dimensional bending through multi-chamber or helically wound elastomeric structures, have also been explored for agricultural gripping. The seminal work by Martinez et al. [125] dates back to 2013 and anticipated the subsequent research boom in this field by several years. More recent designs have applied similar principles to fruit handling [126], albeit with limited force output and durability. Becker et al. [127] exploited an array of slender hollow elastomeric filaments that behave like tentacles to leverage entangling strategies and simplify control.

Regarding volumetric-expanding grippers, they are composed of soft bladders whose volumetric deformation enables outer or inner grasping. Tasneem and Oka [128], for instance, designed a two-bladder stem holder for sweet pepper harvesting. A similar approach has been used by Navas et al. [129], who proposed a gripper with a set of volumetric-expanding actuators arranged in a triangular or semi-circular layout.

Regarding twisting grippers, this motion is mainly exploited to generate grasping forces. In the work by Yang et al., for instance, the twisting motion is obtained through a spiral hollow channel inside a cylindrical structure, with a maximum measured twist of 540° [130]. A combined bending–twisting motion was achieved by Yin et al. [131] by combining a bistable steel shell with a helical plastic structure, successfully lifting loads up to 90 N. In this case, pneumatics serves as the actuation to trigger the transition between the two stable states (straight, wrapped) of the SPA.

In the case of linear SPAs, they are used to generate high grasping forces, but the nature of their deformation makes them generally less interesting than bending systems. In order to exploit the high force-to-weight ratio of a linear SPA combined with the high adaptability typically required in soft robotics, the authors recently proposed the BiSoft.Q gripper, formed by a 6-bar planar linkage driven by a compliant and bi-directional linear SPA capable of generating both closing and opening grasping forces [132,133]. A similar solution was also proposed in [134] with a combination of a bellows and soft bending fingers, but with an outer grasping mode that can be enabled only by vacuum.

Beyond the use of soft grippers driven or entirely made of soft actuators, two alternative solutions exist: suction gripping and jamming. Regarding the development of soft pneumatic suction grippers, the two strategies explored involve the series combination of multiple small-sized suction cups arranged on a soft bending finger [135] or parallel configurations [136,137]. In the case of jamming-based grippers, granular jamming systems are mainly exploited, where a granular material contained in a flexible and non-porous bladder undergoes a reversible transition between a low-stiffness fluid state and a high-stiffness solid state caused by the application of vacuum [138]. Recent examples applied to agriculture include the jamming donut gripper by Joseph et al. [139], which has an annular shape and has been tested on crops of different geometries and sizes; the dual-chamber finger by Peng et al. [140], which combines positive gauge pressure for finger bending with vacuum-driven granular jamming to control gripper stiffness; and the Xeno-Tongue Gripper by Gilday et al. [141], which uses a vacuum-driven bellows for initial crop engagement to press it against a suction cup whose stiffness is regulated by granular jamming, also demonstrating great capabilities in food handling without damaging the object.

Unlike pneumatically actuated exoskeletons of industrial derivation, the application of soft wearables in agriculture is still little explored, with few examples reported in the recent literature [142]. This is probably due to the lack of real advantages in adopting such architectures compared to alternative tendon-driven or compliant mechanism solutions.

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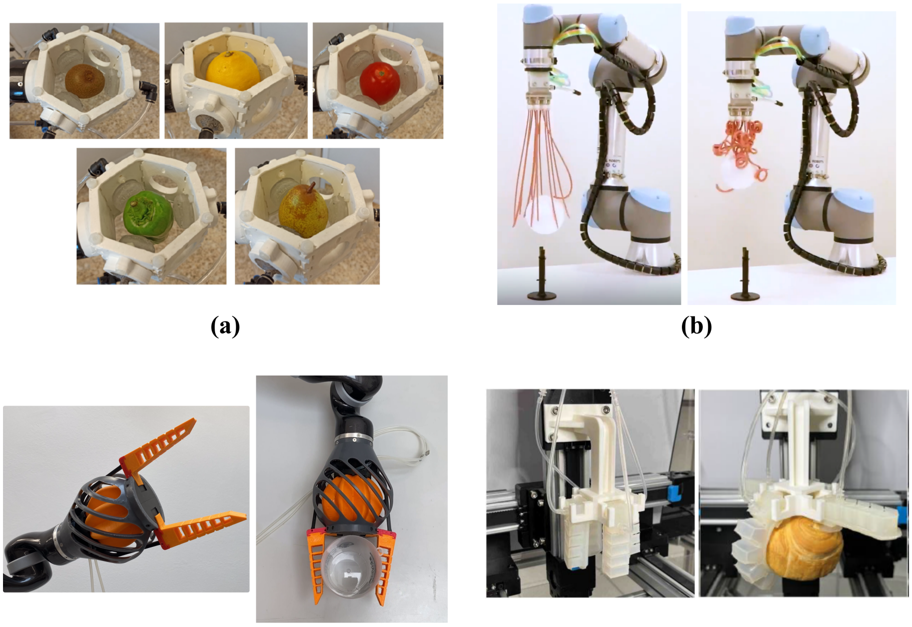

(a) (b)

(c) (d)

Figure 5. (**a**) Gripper for precision harvesting in the triangular layout. Adapted from [129] (CC BY 4.0). (**b**) Gripper made of fluidically actuated slender hollow elastomeric filaments for active entanglement. Adapted from [127] (CC BY 4.0). (**c**) The BiSoft.Q compliant and bi-directional gripper [143]. (**d**) Soft pneumatic bending gripper with embedded suction cups. Adapted from [135] (CC BY 4.0).

4.3. Pneumatic Soft Robotics for Inspection and Surveillance

The application field of inspection and surveillance is one of those that has benefited the most, in terms of scientific output, from the trends of soft robotics [28]. The main interest here lies in the development of mobile robots based on biomimetic or bio-inspired locomotion principles enabled by the combination of additive manufacturing and innovative materials, with the advantage of achieving more robust navigation in unstructured terrains. Unlike traditional pneumatics, where an actuator allows the control of an actuated joint, the use of soft actuators enables the creation of embedded structures where the actuator itself becomes the locomotion element. For snake-like robots, for instance, several examples concern the design of embedded systems for generating rectilinear locomotion as shown in Figure 6a [144], sidewinding [145,146] in Figure 6b, helical [147], and travelling wave [148]. Examples of worm-like robots instead create peristaltic movement [149,150] or crawling [151].

Despite this body of literature, it should be noted that a limited number of examples of worm-inspired mobile robots have been applied in real-case scenarios, such as the work by Liu et al. [152] from 2022 or that by Zhang et al. [153] from 2018 or, the work by Zhao and Luo [154] from 2024.

A parallel and rapidly growing field concerns the development of soft pneumatic robots for underwater navigation and manipulation. Regarding the former aspect, research focuses on the development of bio-inspired structures, such as the soft ray proposed in [155] actuated by 12 bionic soft fins capable of generating undulatory propulsion, or the robotic fish by Ling et al. [156] equipped with a soft fin driven by an integrated oscillating pneumatic circuit, or the underwater robot by Chen et al. [157] featuring bending SPAs that enable it to swim or crawl on the seabed. The field of soft pneumatic underwater robotics is also rich in soft arms and grippers for the retrieval of artifacts or animals, as in the case of the soft gripper by Wu et al. [158] in Figure 6d inspired by the glowing sucker octopus, or the flexible manipulator by Zhang et al. [159] used for detection tasks.

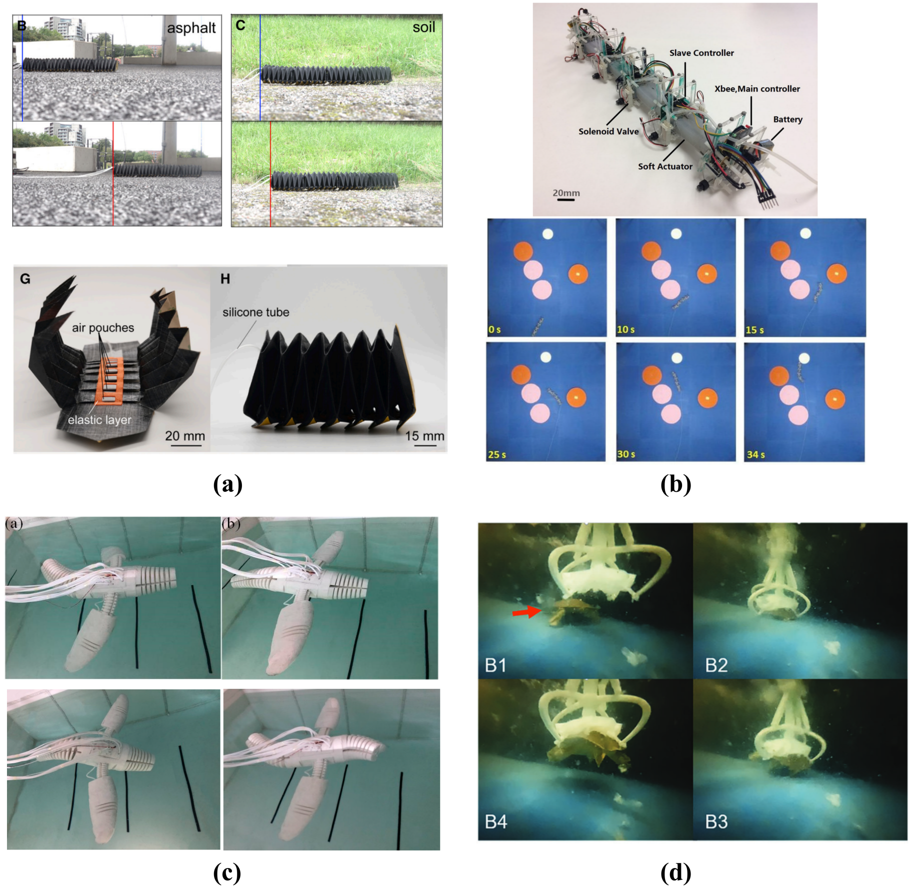

Figure 6. (**a**) Origami snake robot driven by pneumatic pouches. The robot moves on asphalt (B) and gravel (C); the robot's inner air pouches are shown in the cross-sectional plane (G), while the robot is shown in the longitudinal plane (H). Adapted from [144] (CC BY 4.0) (**b**) WPI SRS pneumatic robot whose unit module is composed of four bi-directional bending SPA capable of avoiding obstacles (red and pink objects) to reach a target point (white object). Adapted from [145] (CC BY 4.0). (**c**) Amphibious pneumatic soft robot with bilateral flippers, tail swinging and dorsal-ventral motion. Adapted from [160] (CC BY 4.0). (**d**) Bio-inspired soft gripper with embedded suction cups for underwater exploration, shown during the approach (B1), grasping (B2), lifting (B4), and release (B3) phases of a target animal, highlighted by the red arrow. Adapted from [158] (CC BY 4.0).

4.4. Pneumatic Soft Robotics for Search and Rescue

For search and rescue applications, the adoption of soft pneumatic technologies has enabled the development of growing robots that navigate by everting a flexible tube from a fixed base, soft manipulators and grippers for debris removal, and, in minor number, wearable devices to assist rescue personnel.

A particularly promising category is that of growing robots [161,162]. These devices can navigate by gradually deploying a flexible tube from a fixed base, which allows them to grow through narrow gaps and around obstacles without needing traction on the surrounding. The RoBoa system represents a notable example, for it uses pneumatic pressure to extend a soft, textile tube up to 10 m, potentially enabling two-way communication with trapped victims [163]. A similar concept is embodied by the Sprout vine robot which is designed to explore voids under collapsed structures and map potential ingress routes for rescuers with a total tested reach of 3 m [164].

Soft manipulators have been developed specifically for debris removal in collapsed terrains. Notable examples are the giant anteater-inspired manipulator by Wen et al. [165], which was explicitly tested for navigating narrow passages in rubble; the OctArm series of octopus-inspired soft manipulators [166], which have been explored for search and rescue operations; and the recent octopus-inspired soft pneumatic robotic arm by Papadakis et al. [167], designed for manipulation in unstructured and confined environments typical of disaster sites.

5. The Role of Materials and Manufacturing Methods

Soft robotics is evidently an extraordinarily vast and multidisciplinary field, where the design limits are imposed by the materials used as well as the related manufacturing techniques. Figure 7 summarizes, in tabular form, the main production processes and the related materials employed in the creation of a soft pneumatic robot.

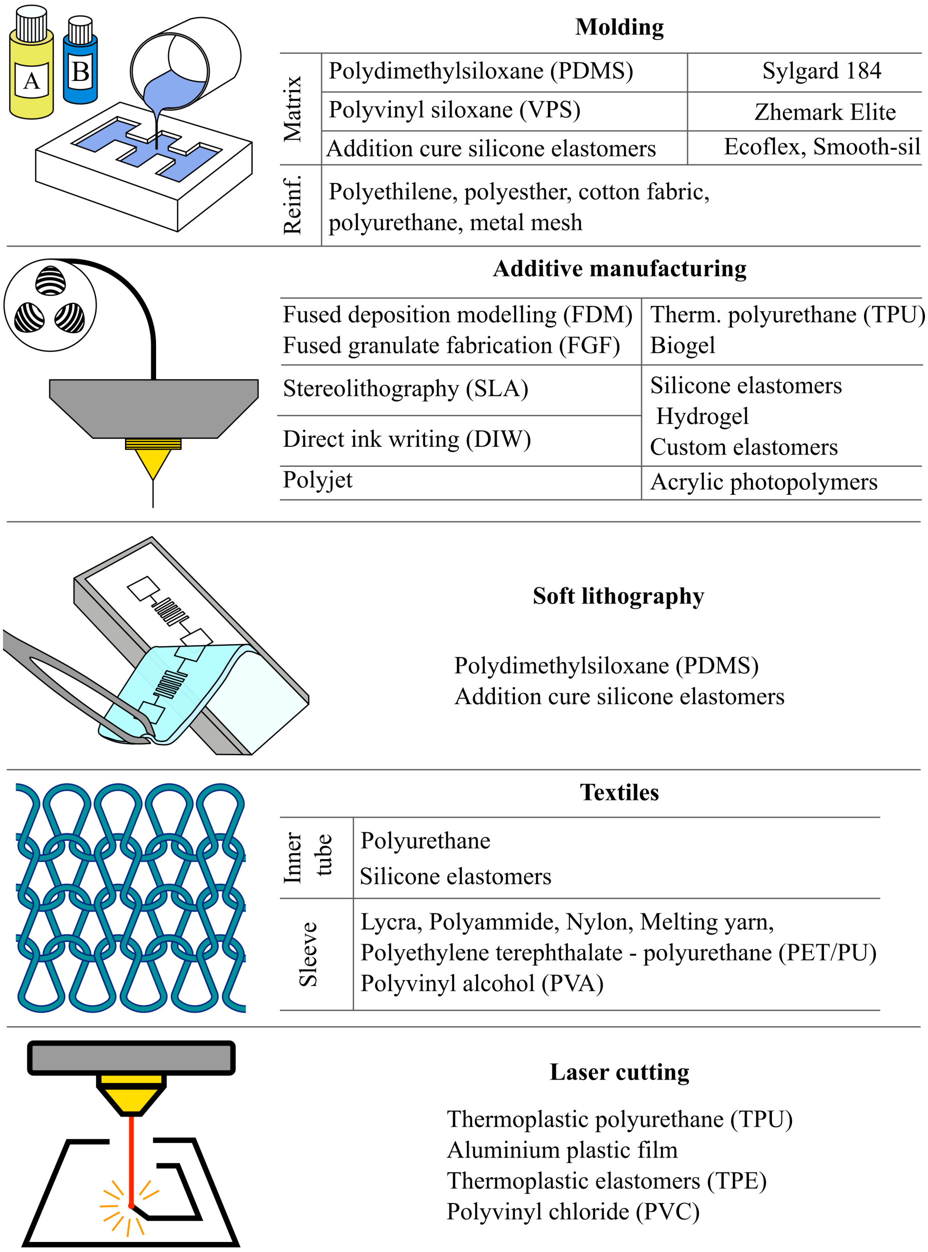

Figure 7. Materials and methods used in the manufacture of soft pneumatic robots.

5.1. Molding

The first technique that is worth mentioning is the molding of highly elastic materials. While in the past, the production of molds was a critical aspect of this technique, this is nowadays largely solved by creating the molds in rigid plastic material using additive manufacturing machines (typically Fused Deposition Modeling, FDM). Molding is, in fact, one of the most accessible and cost-effective methods for producing pneumatic soft robots [29]. Ilievski et al. [168], for example, realized a pneumatic bi-directional and multi-material soft bending gripper by using polydimethylsiloxane (PDMS) for the central layer, which bends but does not undergo large deformations, and a siloxane, with a higher maximum strain rate, for the chambers of the various pneumatic actuators that make up the gripper. Similarly, Morin et al. [169] used the same basic unit, i.e., a PneuNet actuator, to create a fluidic planar walker with additional camouflage capabilities.

Han et al. [170] instead created a pneumatic soft bending actuator through a circular soft chamber made of silicone rubber and a constraining frame made of polyurethane. The actuator was then used to create the gripper, and the physical principle of granular jamming was employed to stiffen the actuators once they are in contact with the object to be grasped. López-Díaz et al. [171] developed a similar solution, but made from hydrogel, which also shows self-healing capabilities.

Another remarkable example is the work of Bell et al. [172], in which a double-acting PneuNet actuator is integrated with a peristaltic pump to obtain a compact and untethered actuation unit. In this case as well, the actuator is fabricated through injection molding of a silicone elastomer, but the constraining material consists of a thin metal mesh.

Jones et al. [173] created a class of soft pneumatic actuators using bubble casting. This method is based on the complete filling of a mold through the injection of vinyl polysiloxane (VPS). The internal channel is then formed by injecting air, which, due to gravity, tends to float in the VPS, creating an internal channel whose axis of symmetry does not coincide with that of the VPS structure. Once cured, the final result consists of an element with anisotropic behavior when pressurized.

Finally, there are examples where the internal chambers of a molded soft pneumatic actuator are filled with a porous rubber, which is obtained using a silicone elastomer as a matrix and salt as a fugitive porogen [174,175]. The presence of foam in the internal chambers of the structure helps reinforce the actuator and prevents uncontrolled volumetric deformation when pressurized.

5.2. Additive Manufacturing

Additive manufacturing represents the other predominant methodology for fabricating soft robots. The review by Sachyani Keneth et al. [176], published in 2021, offers a broad overview, which is expanded here with more recent examples.

The Fused Deposition Modeling (FDM) method is undoubtedly the most widely used technique due to its low cost. It allows the printing of polyurethane (PU) material with different hardness levels (typically 60A–95A), though with lower accuracy compared to other methods. Nevertheless, there are several noteworthy examples, including the PneuNet actuator with internal lattice structures by Lalengani Dezaki et al. [177] or the pneumatic auxetic structure by Eguchi et al. [178], manufactured using Fused Granulate Fabrication (FGF), which extrudes granules of material instead of a filament.

Although FDM is typically cited for the fabrication of soft robots in PU, Heiden et al. [179] proposed, in 2022, the fabrication of actuators using a fully biodegradable gelatin-based hydrogel (biogel).

Conversely, Stereolithography (SLA), which consists of the selective polymerization of a liquid resin using a laser beam, generally achieves more accurate results than FDM, both in terms of nominal layer resolution and the actual printed object. It can be used for the fabrication of objects in hydrogel [180], silicone [181], photopolymers [182], or custom elastomers [183–185].

SLA shares with Direct Ink Writing (DIW) a high adaptability for printing materials of different natures, but it also offers the additional capability of multimaterial printing [176]. Schaffner et al. [186] developed custom silicone-based printable inks with different elastic properties and used them to fabricate soft multimaterial actuators. Cheng et al. [187] instead created a biomimetic pneumatic tentacle using hydrogel ink. Finally, Wang et al. [188] used silicone-based inks for multimaterial printing in a support matrix, which eliminates the problem of overhang angles and thus allows for the creation of even more complex geometries.

The polyjet technique represents another option for multimaterial printing. Sheng et al. [189] developed a soft crawling robot inspired by caterpillars. The soft material used is an acrylic photopolymer with a maximum strain of 140%. To enable forward motion, the robot's contact elements with the ground consist of anisotropic feet, combining rigid and soft materials. Kappel et al. [190] used similar methodologies to build a bending actuator and then compared it with the same actuator manufactured via FDM. The result showed that the polyjet-made specimen exhibited lower elasticity and reduced fatigue resistance compared to the FDM version, a finding also confirmed in [188].

5.3. Soft Lithography

In the case of millimeter-scale soft systems, additive manufacturing techniques are unsuitable, and soft lithography is employed instead. The outcome of such processes typically consists of pneumatic small-scale soft structures made of silicone elastomers, generally PDMS. In a recent study, Milana et al. [191] developed an array of soft and flexible microactuators acting as artificial cilia, which could be used for micropumping or micromixing tasks. The authors designed a micromold that enables the molding of 36 microactuators in a single casting, each with an outer diameter of 150 μm and a length of 450 μm. Another remarkable work was presented by Russo et al. [192], where the soft lithography process was used to fabricate soft fluidic microactuators in biocompatible silicone elastomers with proprioceptive sensing capabilities. This work was later expanded upon by the same authors for the fabrication of a 12-layer soft spider in PDMS [193], featuring multiple degrees of actuation.

5.4. Textiles

Another approach involves the use of knitting techniques, adapted from the garment industry, for the fabrication of outer constraining sleeves for soft airtight chambers. The achievable geometries are evidently more limited compared to additive manufacturing techniques (restricted to rectangular or cylindrical shapes), but sewing proves to be a simple and reliable process, which is why several noteworthy studies can be found in the literature.

In the work of Elmoughni et al. [194], the airtight bladder is made of laser cut PU sheets, welded together with an impulse sealer, while the outer shell is manufactured using a garment knitting machine with materials such as Lycra or polyamide. Yang et al. [195] developed a monodirectional bending/unfolding actuator that combines, for the outer sleeve, a conductive layer for deformation self-sensing and an elastic layer that acts as a recovery spring. A similar approach, but with a different knit geometry, is used by Luo et al. [196], employing a Lycra yarn. A recent study by Wang et al. [197] from 2024 discusses the effect of different knitting techniques on the behavior and performance of bending soft pneumatic actuators. Finally, Sanchez et al. [198] utilized acrylic, elastomer, and polyvinyl alcohol to create a family of seamless and monolithic sleeves for soft manipulators and mobile robots.

5.5. Laser Cutting

In the case of flat or origami-inspired structures, it is possible to construct soft pneumatic robots using laser cutting. In this approach, flat soft bladders are cut by a laser beam and then sealed together. For example, Amiri Moghadam et al. [199] used TPU to fabricate a thin soft gripper and a four-arm swimming robot. In this case, the TPU layers were stacked, and the laser beam performed both the membrane cutting and the sealing of the internal chambers. Shen et al. [200] developed a flat pneumatic artificial muscle with a similar laser cutting/welding technique, employing an al-plastic film that withstood a maximum pressure of 200 kPa (gauge). The pneumatic bladder was constrained by an outer mesh made of polyethylene terephthalate, also laser-cut, and Kevlar wires.

Rogatinsky et al. [201] proposed a soft robot for constrained environments made of stacked balloon actuators. Each balloon was fabricated by stacking two layers of thermoplastic elastomer, which were selectively sealed through selective heat pressing, while a Teflon intermediate mask was used to preserve the internal chamber. Chen et al. [202] developed an origami-inspired bending actuator using laser cutting, with TPU as the sealing layer and polyvinyl chloride as the structural layer. The two layers were joined together using double-sided adhesive tape and subsequently heat-pressed along the edges. A similar approach was presented by Li et al. [203] for the fabrication of stacked balloon actuators.

6. Discussion and Future Perspectives for Pneumatic Soft Robotics

From the presented discussion, it is clear that soft robotics has profoundly changed scientific research and it has introduced a new way of interpreting the use of pneumatics in service robotics. With the exception of a few specific fields, such as MRI-compliant robots and construction robots, soft robotics has enabled the expansion of pneumatic solutions across all the application domains defined by the IFR.

Despite the narrative nature of this review, the overall numbers of the papers discussed (Figure 8) allow for a few observations. The medical and agriculture sectors are the most mature, with a weight of 41% and 27% of the scientific output on soft pneumatic robots analysed here, confirming that they still represent the fields of greatest interest. Agriculture has also increased its relative weight compared to traditional pneumatic systems, mainly due to the larger number of compliant gripping devices. Regarding inspection, the total number of papers has increased (17 contributions, equal to 23% of the soft sample), a sign of growing interest, especially in bio-inspired mobile robots. The search and rescue sector confirms itself as a niche, with only 9% of soft contributions.

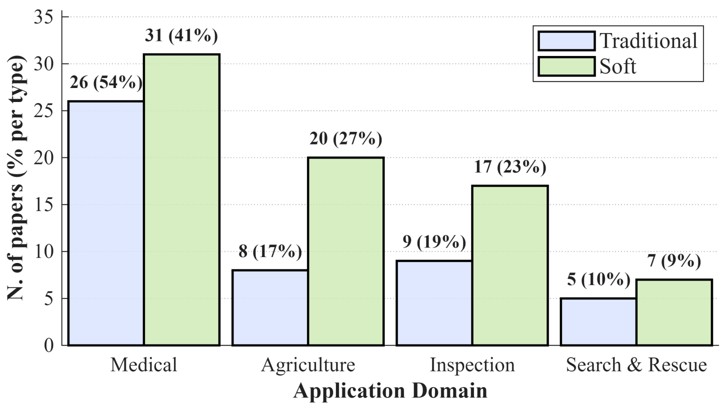

Figure 8. Distribution of traditional and soft pneumatic robots across four IFR application domains discussed in this narrative review. Percentages indicate the relative weight of each domain within the respective category (traditional or soft).

6.1. Monolithic Fabrication and Multi-Material Manufacturing

Among the cross-cutting open issues, the development of monolithic structures is particularly relevant. The manufacturing methodologies described in Section 5 aim at obtaining complex geometries from deformable materials. However, for pneumatic systems, achieving the intended behaviour is strongly linked to the placement of reinforcement material, which must guide deformation, prevent uncontrolled volumetric expansion, and ensure airtightness. Moreover, operating pressure is merely a parameter that scales the force–elongation isometric curves of a soft actuator [143]; therefore, the quest for higher performance translates, among other things, into a quest for stronger structures. From a technological viewpoint, this remains one of the most investigated problems for researchers working on monolithic structures.

A single-material monolithic structure inevitably represents a trade-off between robustness and deformability, with limited possibilities to counteract uncontrolled volumetric expansion except by varying wall thicknesses [204,205]. Consequently, multimaterial soft structures are a widely explored solution. Drawing from the previous analysis, the most promising multimaterial fabrication methods come from additive manufacturing, because they eliminate the need for molds and do not constrain the achievable geometry. Direct Ink Writing (DIW) enables the creation of monolithic structures with stiffness gradients and also overcomes overhang issues [186,188,206]. Polyjet printing also allows multimaterial fabrication, but it imposes constraints on viscosity, surface tension, and evaporation rate, limiting its application to the few commercially available acrylic photopolymers.

6.2. Embedded Sensing and Circuit

Embedded sensing is the third key challenge for the real-world deployment of soft pneumatic service robots, alongside monolithic fabrication and durability. The objective is to equip soft robots with both proprioceptive awareness of their own state and exteroceptive sensing of the environment, without compromising their core compliance.

In this sense, pneumatic soft robots have the clear advantage that the back-drivability due to air compressibility can be exploited to estimate contact forces and robot state. For instance, pressure signals alone have been used to infer applied forces in soft actuators with good accuracy, relying only on external pressure sensors [207,208]. More advanced approaches use fluidic multichambered actuators to achieve multi-axis intrinsic force sensing by mapping pressure variations to external loads [209]. This type of measurement is simple and often robust enough for basic applications, but the uncertainty of the forces acting on a soft structure that can deform in complex ways limits its use to specific contexts.

Although the physical principles are well known, current research focuses on embedding sensors directly into soft structures. For instance, additive manufacturing enables the embedding of air channels and housing for miniature pressure sensors and inertial measurement units directly into soft robot segments, allowing for proprioceptive sensing without compromising the structure elasticity [210]. Fabric-based actuators represent a category in which sensor integration is relatively straightforward, as resistive strain sensors can be directly integrated into the textile structure, thus offering a low-cost and scalable route to sensorized soft robots [211,212]. Tactile perception is another rapidly growing area: soft pneumatic [213] or electric [214] tactile sensing matrices have been proposed to estimate the contact area and force.

6.3. Control Circuitry

Finally, the control infrastructure remains a bottleneck for most soft pneumatic robots. The presence of compressors, valves, and auxiliary volumes is often cited as the hidden, bulky counterpart of every lightweight soft pneumatic robot, rarely accounted for in force-to-weight ratios and fundamentally at odds with the goal of fully soft and compliant structures. In this sense, the true limitation of soft pneumatic robots is not their mechanical performance, but the lack of equally soft and integrated control systems.

To address this, researchers are actively working on integrating circuitry and actuation in a manner consistent with soft robotics trends. Examples include the bistable directional valve based on the snap-through principle [215], the family of pneumatic logic valves proposed by Decker et al. [216], additively manufactured components for the control of a walking robot [217], and the bistable fabric mechanism by Yang et al. [218]. A further step towards autonomy is the development of standalone, portable driver units that combine pumps and valves, eliminating external air supplies [219] or embedding valves directly into McKibben actuators to remove external regulators [220].

Further challenges arise from the need for soft compressors capable of generating a pressure gradient without rigid mechanical components. Although the field is still in its infancy, the first fully flexible integrated pumps are emerging, for instance based on electrostatic origami chambers [221–223].

Nevertheless, the issue of energy autonomy remains largely unsolved, and the trade-off between portability and actuation performance is still a major obstacle. Achieving a truly soft, fully untethered, electronics-free pneumatic robot that can operate reliably in real-world IFR domains remains an open challenge.

6.4. Durability and Operational Lifetime

Although many soft pneumatic robots show promising behaviour in laboratory settings, very few studies address their long-term durability, severely limiting their real-world applicability in service robotics. The field has seen a highly creative phase of conceiving new geometries and actuation principles, but there is now an urgent need to focus on the robustness of what has been produced. This lack of systematic assessment implicitly relegates most works to exploratory research and delays practical deployment in IFR domains, i.e., medical devices, agricultural fields, and inspection sites, where exposure to dirt, moisture, repeated loading, and unpredictable external factors would rapidly degrade unprotected soft structures. Existing endurance tests, still limited in number, reveal significant performance degradation over time even in controlled laboratory settings [224,225], highlighting that material fatigue, delamination, and air leakage remain unresolved issues.

A parallel direction is the use of self-healing materials to extend operational life. Self-healing polymers—based on either intrinsic (e.g., reversible covalent bonds) or extrinsic mechanisms—have attracted attention for soft pneumatic systems [226,227]. More recently, digital light printing has enabled the fabrication of soft robots with complex air chambers that self-heal cuts and punctures at room temperature, achieving healing efficiencies above 87% [228]. Nevertheless, the healing performance, i.e., healing time, recovery strength, and number of repair cycles, is still far from demonstrating the solidity required for practical service applications.

Taken together, durability is no longer a peripheral issue but a central research bottleneck. Future progress requires standardized fatigue testing protocols, robust fabrication strategies, and a shift from proof of concept approach to systematic lifetime validation.

7. Conclusions

This paper has reviewed pneumatic robotic solutions by providing an application-oriented reading across the various service robotics sectors defined by the IFR. The major trends in the 1995–2018 period have been highlighted for each application area, explaining the advantages of adopting pneumatic technologies. Subsequently, the advent of soft robotics has been described, showing how it has revolutionized research directions and what the main drivers of this change have been. A specific section has been devoted to the role of manufacturing technologies available in research laboratories and their effect on the design of soft robots. Finally, the key drivers shaping current research have been identified, and the open challenges that still prevent the widespread deployment of soft pneumatic service robots in real-world scenarios have been discussed, together with future perspectives for bridging the gap between laboratory prototypes and field applications.

Focusing on the IFR application domains that have provided structure and framing to this review, soft pneumatic robotics has now proposed solutions on almost all fronts. However, a significant technological gap still separates research from real-world deployment, with many technologies still in a purely exploratory, early-stage phase and lacking explicit validation in real-world contexts. The open challenge for researchers is therefore to translate the remarkable creativity of soft pneumatic robotics into robust, reliable systems with clear advantages over their traditional counterparts, so as to operate alongside humans in the unstructured environments of service robotics.

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