Soft Medical Robots and Probes: Concise Survey of Current Advances

MOSTAFA SAYAHKARAJY*, HARTMUT WITTE
Fachgebiet Biomechatronik
Technische Universität Ilmenau
98693, Ilmenau
GERMANY

Abstract: - Soft robotics has emerged as a new branch of robotics gaining huge research interest in recent decades. Owning intrinsic advantages such as compliance and safety, soft robots are closely associated with the medical requirements of medical robots. This review is written to overview advances in the medical applications of soft robots, either for readers primarily familiar with traditional medical systems, or for researchers planning to develop soft robots for medical applications. Recent publications related to soft medical robots were reviewed to represent the state-of-the-art advances in this field. The review tends to compress the scope to trunk-shaped soft robots and appraise the status of soft robots and their distance from clinical use. Several papers related to the construction and capabilities of soft robots were referenced. Roughly 190 related articles published in the current period from 2018 to the publication date (representing almost 90% of the references to the theme totally identified) were reviewed. Structure of soft robots, advances in technology, and the aptitudes in medical applications were discussed. The trunk-like soft robots conspicuously are proposed for applications including robot assisted surgery where a probe is inserted into the human body. Such robots are also present in other medical robots as actuators. The literature shows that different methods are used to fabricate soft robots and employ them in different robotics tasks including positioning, grasping, and force exertion. Noticeably, such studies were done in robotics laboratories, dealing with robotics engineering problems. This review suggests that the technology is actively developing, but further focus on specific medical applications is required to fill the gap between soft robotics and its clinical use.

Key-Words: soft robotics; medical systems; soft pneumatic actuators; medical probes; continuum manipulators

Received: October 11, 2023. Revised: November 4, 2023. Accepted: November 23, 2023. Published: December 31, 2023.

1 Introduction

Nowadays, robots are found in various areas aiding monotonous, accurate, and physically demanding tasks as needed by humans. From a robotics engineering point of view, the most commonly known robot types include robot manipulators, which consist of some links connected together with rotational or linear joins, and mobile robots, which can be described as wheeled devices designed to autonomously move to desired locations. However, the structure and functionality of medical robots is very different from industrial robots. In fact, we need to refer to standard definitions to nominate a medical device as a ‘medical robot’. Various medical robots are meant for different purposes from rehabilitation, prosthetics, disinfection, hospital or pharmacy automation, to surgical and telepresence robots.

Naturally, different designs and working principles are used to achieve different purposes or intended uses, resulting in the large diversity of medical devices. Nevertheless, a group of medical robots and probes such as echocardiography probes have something in common so that roboticists can classify them into one group. The common part is an insertion tube that consists of serially connected links that are manipulated by tensioning cables implemented inside the probes. Basically, such structures have evolved to minimize the ratio of the insertion probe diameter to the hole through which the probe is sent to the patient’s body. Such systems are essentially cable-driven manipulators and mathematically share the kinematic equations of robot arms.

Presently, only a few advanced robots are practically employed for invasive or semi-invasive medical purposes, and many more systems are still in the process of getting approval for clinical use. The medical robots contain cable-driven endoscopic devices as end-effectors [1, 2]. Modern robotics advances in surgery include minimally invasive surgery robots, single port surgery and natural orifice transluminal endoscopic surgery robots, and non-minimally invasive robotic systems [3]. Review articles listing surgical robots have been published in [4, 5]. They introduce the industry and firms contributing to the production of medical robots, referencing their clinical use status (CE/FDA approval, human trial, *etc*.), and list commercially available systems. In addition to robotic surgery, endoscopy is an important method of imaging in medicine [6].

In the recent two decades, scientific publications on robotics have witnessed exponential growth in the number of articles and impact factors on a new field named soft robotics. The first soft robots used artificial muscles known as McKibben actuators, which consist of a reinforced elastomer tube that contracts when pressurized pneumatically [7]. Since then different soft robots with various methods of fabrication, actuation, and manipulation have been developed. The material compliance of soft robots makes them interesting for delicate applications from grasping an apple [8, 9] to robot assisted echocardiography [10]. Such trends attract attention of developers of medical devices and intrigue questions that can be best explained by a review of the publications in this area.

Existing reviews show tremendous growth of soft robotics, fabrication methods, and the modelling and control methods. Reviews include general medical devices [11], covering soft robots proposed as various medical robots such as minimally invasive surgery robots, rehabilitation systems, and assistive devices. Due to specification variety, soft robots can be viewed from various points of view and specified reviews are required to address specific scopes and objectives [12, 13]. In this context, we investigate recent advances in soft robotics related to medical probes and insertion manipulators. The specific focus is on pneumatically driven elastomeric robots. The target is to provide an introductory overview for either those biomedical engineering researchers who are not familiar with soft robots, or soft robotics researchers and mechatronics developers who are interested in the medical applications of soft robots.

2 Technical Scope of Soft Robotics

The rapid growth and wide spread of soft robots resulting in various types, applications, and even different terminologies used in the literature make definition of soft robots harder. The first question to be answered regarding soft robots is what is technically meant by the term soft? In fact, different physical phenomena might be related to softness. Classically, mechanics has defined parameters such as bending stiffness, elasticity module, and surface roughness precisely with mathematical terms, but softness appears a vague word. The term ‘soft’ in this context most often refers to non-metal materials with low hardness from which the soft actuator or robot body is fabricated. This follows the definition given in [14]. However, it does not mean that all soft robots are made completely out of silicones, though this definition makes soft robots recognisable from flexible manipulators [15] where mechanical compliance is the result of the slenderness of the links that are made with conventional engineering materials. Similarly, methods of fabrication of soft robots have evolved in a way that is, to some extent, differentiable from conventional robots. Soft robots are fabricated with various methods including rapid prototyping or 3D printing [16-20], origami-based techniques [21-23], Kirigami (which is a paper cutting art) [24], folding [25] and sewing textile layers (fabric-based system), [26, 27], everting tubes [28-31], bellow type approach [32-34] and casting in 3D printed mould [35, 36], *etc.* In [37] the moulding methods are classified as retractable pin based, lamination based, and lost-wax-based methods. A sort of laboratory soft actuator is made by casting soft material in moulds, and reinforcing them by inserting strings [38, 39]. The strings are often twisted into repeating shapes to yield different motions [40, 41]. By weaving the fibres around the soft tube, rapid production of this type is possible [42]. As in [43] a fibre-reinforced soft actuator can also be made with 3D printing.

Alternatively, the soft actuator can be printed out of a single material in which some chambers are implemented to cause bending action [46]. Direct 3D printing of silicone elastomers is effective for prototyping multi-chamber soft robots [44, 45]. Designing fibre alignment for achieving the desired motion is still an active research topic [47]. Some methods have been developed to trigger 2D sheets of stimuli-responsive materials into 3D soft actuators. The main smart materials, which are carbon nanomaterials, shape memory polymers, metal nanomaterials, azobenzene, liquid crystal polymers and elastomers, hydrogels, and bio-hybrid materials are reviewed in [48]. Fundamentally, various types of actuation energy are used in soft robots [49]. Positive or negative (vacuum [50]) pressurizing is the most common with pneumatic or hydraulic soft actuators [51, 52]. Some methods include thermal actuation of liquid crystal elastomer (LCE) soft materials, by direct environmental heating [53], by light [54], or by electrical heaters [55]. In tendon-driven soft robots [56, 57] a soft beam is actuated mechanically by pulling a string passed through the soft trunk. Jamming is the principal working element for many of the actuation systems [58], including electroactive polymers (EAPs) that deform under an electric field, fluidic actuators, shape-memory materials (SMMs), electro- and magneto-rheological materials (fluid or elastomers) (ERMs and MRMs) [59], and low melting point materials (LMPMs), which show stiffness change with varying temperature [60, 61]. A comparison between some common actuation methods is illustrated in Fig. 1. The pneumatic soft actuators have the advantage of low weight and low noise which makes them interesting for medical applications. In terms of high-power output and payload capability, and low power consumption they are compatible with cable-driven systems. Based on this background, pneumatic soft actuators can be a good candidate to perform the tasks of traditional medical cable-driven end-effectors, with a further advantage of softness and the consequent human interaction safety. This fact is observed in the literature, as will be discussed later in this review, to the extent that the term ‘soft’ generally refers to elastomeric soft robots actuated with fluids, either hydraulically or pneumatically.

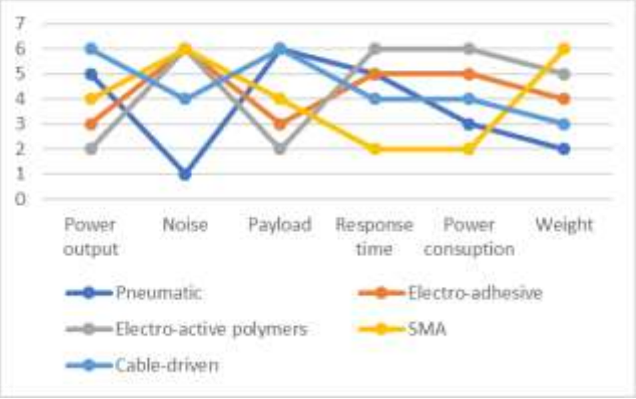


Fig. 1. Comparison of different grippers with various actuation methods scaled from zero for poorest to 6 for the best (Data according to [52])

2.1 Soft Actuators vs. Soft Robots

An explanation for distinguishing soft actuators from soft robots can be instructive in many cases. First, note that soft robots often contain continuous parts without normal joints, and so, the border is not completely distinguishable. In this context, the phrases are employed interchangeably with a minor alteration that ‘soft actuator’ accentuates a single working actuator which can be an element of a more complex soft system or robot with controllers and other elements. Additionally, an actuator normally acts in a single DOF (bending, contraction, or rotation [62]), while robots are multi-DOF systems employing multiple actuators. For example, in [10] a manipulator with flexible links is designed that uses McKibben pneumatic muscles as its soft actuators. By stacking soft actuators in various patterns, soft robots with more complex abilities such as swallowing or different locomotion or manipulation tasks are achieved [63]. However, it is still likely that a multi-DOF soft robot is made as a continuous part, *e.g.* by casting in one single cast [37], and on the other side, a soft actuator may be designed for several tasks [64, 65]. The cylindrical soft actuators which can be programmed for bending in different directions, as in [55], may be used as one finger or leg of a more complex robot.

Even though the definition proposed above explicitly characterizes soft robots based on their material and fabrication process, it is still an imprecise account as soft robots may not be limited to given materials or construction methods. Additionally, there are countless designs of soft robots with various topologies and actuation principles that make the definition more complex. Nevertheless, the literature can draw the borders for the scope perspective, allowing the authors to declare their understanding and definition of soft robotics implicitly.

3 Continuum Manipulators

Specific attention in this review is paid to a sort of soft robot known as continuous trunk-shaped soft robots. Intentionally, contemporary articles are reviewed to identify the significance and novelty of the research area, and the state-of-the-art technological advances and existing problems. Historically, continuum manipulators, aka trunk-shaped robots were tendon-driven systems actuated by electrical motors [66]. A quasi-static model of such systems was given in [67]. Accurate dynamics modelling of soft robots is complex and still is a challenge [68]. However, normally a simplified quasi-static model is sufficient as such robots have a low weight and move at slow velocities. Trunk-shaped robots composed of soft materials are also known as continuum robots [69]. Classically, the continuum manipulator with serially connected rigid links has played the main role in robotic surgery and probe insertion in the medical context. Trunk-shaped soft robots can be considered as their soft counterparts and investigated for similar scenarios.

3.1 Trunk-shaped Soft Robots

The elephant trunk is a biological system with astonishing manoeuvrability and manipulation capability. Many different examples can be found in nature possessing a tubular shape similar to the elephant trunk. Likewise, a sort of soft robots can be identified with their trunk-like topology, though various names like a finger-type robot, snake or worm-like robot, octopus robot [70], *etc.*, are used in the literature to refer to them. In this work, such robots are nominated as trunk-shaped systems because their biological counterpart represents all the capabilities of various candidates. Some of the robots deviate from others in this class in terms of their application. Those comprise robots designed for locomotion, which regularly mimic the gait of worms, caterpillars, *etc.* However, their mechanics are relatively alike those of other types in this class. The compliant structure of soft robots makes them suitable for interaction with an unknown environment as in grasping and locomotion [71, 72], as well as crawling (or growing) in geometrically complex spaces [73]. Based on the design, bending soft actuators can perform the bending action in-plane or in a 3D helical shape. A tubular soft actuator can be actuated in a nonhomogeneous way for bending, as well as homogeneously for linear motion [55]. Commonly, elastomer-based trunk-like soft robots are often actuated pneumatically and their directed motion is a result of inhomogeneity implemented either by reinforcement fibres or chambers within the elastomer [74].

3.2 Soft Robots and Force Control

Although in many practical cases there is no external force on the soft robots, some researchers considered the design of tube-like robots able to apply external force or to handle objects. The design and control of an assistive soft robot are presented in [75]. The manipulator was proposed for the automation of showering for the elderly. Such robots need to exert sufficient force to perform the task. In order to produce such forces, which is somehow in conflict with structural softness, methods have been proposed to modulate stiffness for soft robots [76, 77]. Based on various stimuli, the rigidity of some materials is tuned, practically switching between deformability and rigidity [78]. This phenomenon is useful in applications like grasping [79, 80] and medical endoscopes [81]. However, in cases that essentially there is no interaction force, for example in trans-esophageal echocardiography (TEE), a soft robot without stiffening is sufficient. An example of a pneumatic bending actuator with variable stiffness is given in [82]. A low-melting-point alloy is implemented in the actuator to keep the bent shape after releasing the actuation pressure. By melting or hardening the metal using electric heat created in the cables, the bending stiffness of the soft actuator is changed.

3.3 Grasping Task

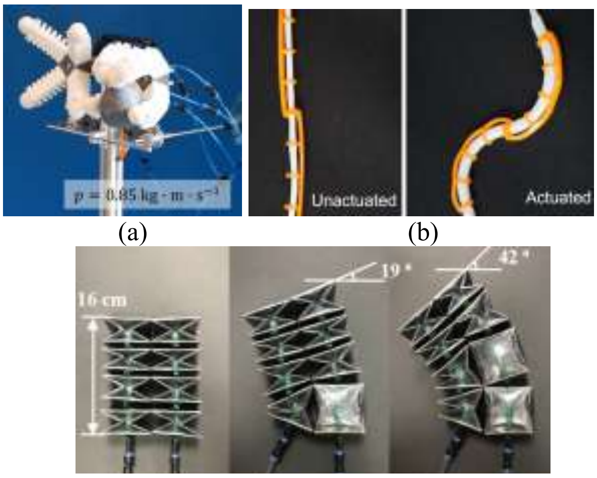
Soft actuators have appeared as efficient end-effectors for grasping objects [83]. The elephant’s trunk can robustly grasp objects of diverse shapes. Many single or multi-fingered [35, 83], grippers have been designed with soft continuous trunk-like fingers. Examples include [84, 85], and [86]. Researchers in [87] implemented a topology optimization method [88], and designed soft fingers using two different materials fabricated by moulding and 3D printing separately. Some soft robots have been developed for the delicate manipulation of deep-sea biological creatures [89]. In [90] a pneumatic control system composed of serially connected proportional and solenoid valves was used to control a multi-fingered gripper. Soft grippers are ideal for harvesting fruits [91]. Many wearable soft robots have been developed by arming a glove with soft actuators. In [92] a glove capable of abduction and adduction movements of the thumb is proposed. Soft fingers have shown limited mechanical performance (such as force and speed), and therefore, some researchers enforced them with a rigid design [93, 94]. Fabric-based soft actuators are used efficiently in developing wearable robots [95]. ‘Exosuits’ can be made with textile actuators as in [96], and [27].

3.4 Positioning Task

The soft robots or actuators intended for position control can be classified in a separate group. In position control of soft actuators, feedback controllers have been practically implemented in [97] to attain 1 mm accuracy of tip positioning for a bending soft actuator. In [98] the bending movement control of a soft silicone arm following a two-dimensional path was presented by employing shape memory alloy (SMA) actuator coils, linear Hall sensors, and PID control. Pressure control of pneumatic actuators is reported in [99]. Feedback control can be designed using the inverse kinematic equation obtained using Pythagorean hodograph curves (as introduced in [100]), as proposed in [101]. Machine learning (ML) methods are also used for the calibration of soft actuators or sensors [34, 102]. Input-output data obtained from experiments on actual prototypes of a soft robot can be used to obtain (*i.e.* train) a data-driven model [103] for simulation or control design, as in [104]. Soft robots are normally highly nonlinear and need calibration. Therefore, ML methods are effective tools for their control.

3.5 Soft Pneumatic Actuators (SPAs)

Soft pneumatic actuators are generally made out of silicon rubbers, and often use asymmetric cross-section, as in multi-chamber types [105], or strengthening fibres to yield a directed motion when pressurized air is supplied (see Fig. 2). Various soft actuators have been designed for performing rotation, contraction, or bending [25, 106, 107]. A McKibben actuator is a type of pneumatic muscle that is attractive for biomedical applications, as in [108], with the advantages of similarity to biological muscles, high safety, and good performance.

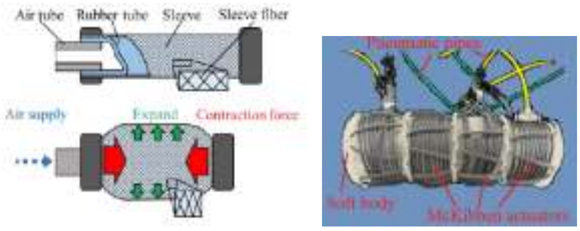


(a) (b)

(c)

Fig. 2. Examples of SPAs with bending function: (a) Silicon-based soft gripper [109], (b) Reinforced McKibben [110], (c) Origami SPA [111]

The actuator consists of a hollow cylinder soft tube, and a braided net [112, 113]. Fabrication of small-size McKibben actuators was proposed in [114]. A McKibben pneumatic muscle is shown in Fig. 3 (a). The design is described in [115]. Currently, some small-diameter actuators with 1.3 mm outside diameter and arbitrary lengths are produced by the Tokyo Institute of Technology. Their model, design, and fabrication have been presented in [42]. As artificial muscles have similarities with biological muscles [116, 117], the actuators are used extensively to develop bio-inspired robots [17, 118, 119]. Recently, a four-segment peristaltic soft robot has been proposed in [120], Fig. 3 (b). Peristalsis is the automatic wave-like movement that move food through animals' digestive system. Generally, McKibben actuators have technological limitations, such as durability or life cycle and fluid leakage that are considered in the development of commercialized actuators. For the tube-like actuators, the user should solve the tricky problems of sizing the actuator and connecting it to the air supply and the soft robot. Another limitation of the McKibben actuators is the contraction ratio that may be dealt with using pulley mechanism designs [121]. Modelling of McKibben actuators has been discussed in [122-127]. Hydraulic power can be used for the actuation of the muscles too [128, 129].



(a) (b)

Fig. 3. McKibben muscles: (a) A type of McKibben actuator [115, 130]. The soft actuator consists of a rubber tube and a braided tube (sleeve) with circular-knitted threads warped around the elastic tube. It contracts when supplied with air. The contraction force depends on the resistance of the external load (boundary conditions), (b) Example application of thin McKibben actuators in a soft robot with peristaltic motion capability proposed in [120].

3.6 Medical Robots

Robotics has been investigated actively to improve medical treatments and healthcare. In applications like robotic surgery where some actuator (*e.g.* gripper) or sensor (*e.g.* ultrasound sensor or optic vision device) is to be sent into the human body, conventional engineering established insertion tubes and end-effectors to access inner organs through the smallest possible holes. Some endoscopes used in surgery through natural orifices and single-port access surgery are shown in Fig. 4. The invasive or semi-invasive devices use wires as their force transmission system, so they are commonly recognised as cable or tendon-driven systems [131-133].

In some minimally invasive operations, the surgeon has to keep the endoscope in their hands for exhaustive periods. In [134], a wireless teleoperation system is proposed as a solution to the problem. Nevertheless, teleoperation conveys additional technical problems and hazards, though it has been suggested for some imaging modalities including TEE [135]. A robotic holder in [136] is proposed to assist the surgeon in handling the endoscope. In the showground of medical robotics, in particular in minimally invasive surgery, keeping the safe contact between a robotic structure and the human body to a high safety level is crucial. High safety conditions are required for the operation of a robotic structure in medical scenarios. Thus, due to their inherent compliance, soft robot systems have the capability of surpassing their rigid counterparts in this scenario.

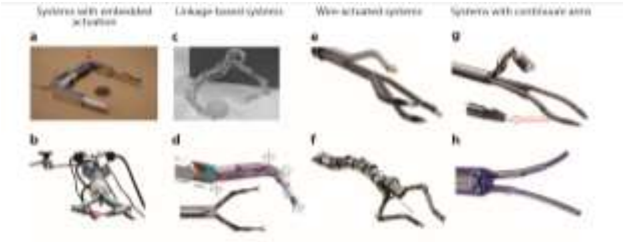


Fig. 4 Surgical end effectors [137]

There is an increasing interest in developing medical devices for various uses including minimally invasive surgery based on advances in soft robotics [138-143]. Recent development of new colonoscopy endoscopes show tendency to replace conventional systems with soft robots [144]. Soft robots with the ability of compliance matching with biological structures are the best candidates for many biomedical applications such as artificial muscle fabrication, muscle alternatives, catheters, prosthetic devices, stents and surgical instruments, and physical therapy or rehabilitation devices [145, 146]. In the literature on soft surgical robots, such as [140, 147, 148], the term ‘soft’ refers dominantly to elastomeric fluidic robots. Recognizing that soft trunk-shaped robots are potentially able to play the role of a medical manipulator, it is not accurate to nominate all of them as medical robots. Thus, in this review, it was chosen to refer to them as trunk-shaped soft robots. Some researchers have proposed medical probe designs with soft structures. A 20 mm diameter (270 mm length) soft probe with bending and elongation abilities is proposed as a laser endoscope in [149]. The soft probe contains three parallel cylindrical chambers working pneumatically. A 6 mm diameter three chamber soft probe is presented in [150]. The authors proposed a fabrication method to make such narrow probes. Soft probes are also developed employing artificial muscles [151, 152], origami bellows [153], electroactive polymers [154], and string-driven design [155]. An endoscope model was proposed in [85] that shows variable stiffness due to the softening influence of heating on polyethylene terephthalate. In conditions in which the robot is exerting forces on the patient’s body, some stiffness is required for the intended use. This requirement conflicts with the softness constraint implied by safety requirements. Some of the solutions for controlling the mechanical strength of medical devices have been reviewed in [156]. The alternative proposed solution, conceptually close to the variable stiffness design, is a shape-locking system. The idea contains a chain of rigid segments that link together serially to make the probe. The inner parts are pushed into the outer links to retain their shape. Commonly, instead of a continuous range of stiffness variability, the target is switched between compliance and stiffness [157]. A conceptually similar requirement is stabilizing (supporting) the soft robot inside body by hardening the base of the robot [143].

Application of soft systems in the context of medical robots is not limited to trunk-like probes. Several assistance and rehabilitation soft robots have been developed [158] using SPAs. Exoskeletons vastly benefit from the advantages of soft robotics [159, 160]. Even though for rehabilitation the robots do not need to replicate the human body structure, researchers show a tendency to make exoskeletons or wearable robots for this usage. Additionally, assistive wearable robots can empower and assist healthy people in performing difficult activities. Such robots are classified as medical robots too because they are required to be safe for the user and have to follow medical and biomechanical requirements. Soft robots are widely studied for such applications. Several hand rehabilitation and assistance robots have been made with soft actuators and materials [161]. Various systems including solid-linkage mechanisms, spring-type flexible fingers, string-driven gloves, as well as pneumatic-driven robots have been developed for finger rehabilitation [146]. Currently, researchers study optimization (or personalization, in better words) of size and mounting position of pneumatic actuators for hand rehabilitation [162]. Research on the applied use of soft prosthetic hands is still a fresh research topic. The robots developed for rehabilitation and the mechatronic devices proposed as prostheses or similar applications are classified as medical robots as they are used in the medical area. However, compared to the endoscopic devices, they can be put in a separate class because of their specific challenges regarding mechatronic sensing of user intent by detection of physical signals of the muscle or nerves’ actions along a motor pathway. Some other mechatronic devices are recognized as medical robots but are not discussed in this review. Examples include robots planned to imitate human or animal cognition, companion robots intended to engage emotionally with users and alert them when there is a health problem, and disinfection robots recently used in the Covid-19 pandemic.

3.7 The Perspective

Admittedly, soft robots still have their own limitations. SPAs, as the focus of this paper, have complex nonlinearities, hysteresis, time-dependent behaviour (creep) [74], material property challenges, and encounter the complexities of fluid control. Perhaps the major limitation is precision or accuracy (in positioning of a tip point, curvature, amount of force, *etc.*). However, state-of-the-art technology is intensively contributing to the development of soft robotics. Countless engineering areas, including augmented reality, optics and image processing, novel actuation and sensing devices, wireless movement transmission systems are just a few examples. The literature shows great attention to human-machine interfaces with flexible and stretchable electronics [163-165]. The technology of deformable electronic systems is growing rapidly [166, 167], and considerable research is devoted to printable electronics for this aim [168-172]. Embedded sensors that can withstand large deformations without affecting the amenability of the actuator are necessary and important for feedback control of soft robots [97, 173]. In [174], a deformation sensor is 3D printed in a multi-chamber pneumatic soft actuator. Additive manufacturing of smart materials, also known as 4D printing, has been implemented in prototyping of many laboratory soft robots [20]. Researchers are developing recyclable elastomers [175], considering material properties for soft robots.

Small power systems are being developed to fabricate cordless soft robots [176, 177]. Researchers developed biomimetic tactile sensors [178, 179] for prosthetic and robot hands [180]. Concurrent research shows advances in texture sensing [181, 182]. Additionally, advances in machine learning (ML) algorithms and computers are improving the precision of soft robots both in actuation and sensing. Researchers are using artificial neural networks (ANN) for modelling soft robots [183], and shape sensing/control [184, 185]. A review of ML methods in soft robotics is given in [186], and [102]. In addition to sensor technology developments, research into developing soft materials for soft robots [187-189] is promising. 3D printing technology for producing biodegradable hydrogel soft actuators has shown promising results [190]. In [191] a small soft gripper (similar to Fig. 2 (a)) was printed using calcium-alginate, which is a biodegradable and edible material. Development of injection moulding of liquid silicone rubber promises mass production of soft robots [192, 193]. The pervasive investigation foresees auspicious prospects for soft robotics.

4 Summary and Conclusions

4.1 Discussion

Traditional medical robots and probes employ high engineering standards with traditional rigid components, while soft robotics deals with new actuation and sensing methods and soft materials and, fundamentally, do not encounter those limitations of traditional robots. Nevertheless, soft robots have their own complexities and limitations. The review of the current literature reveals an increasing research interest in developing and applying soft robot technology for medical use. The trunk-shaped soft robots are investigated to play the role of surgical robots and insertion tubes. Nevertheless, there is a gap between soft robots and their practical clinical implementation. Generally, the advantages and potentials of soft robots in medical usage are renowned in the literature. However, such studies generally fall into the class of basic technology research or technology readiness level (TRL) one to three [194]. On the other hand, precise positioning or force control of soft manipulators is complex due to the nonlinearity of the material or geometry and large deformations. The majority of articles, if not to say all, deal with the latter problem which is still in the context of robotics and mechatronics. Soft robots have various topologies, actuation systems, sizes and scales, and gesture capabilities. For any specific use, the soft robot design and control, or actually the feasibility, should be revisited considering the specific requirements such as dimensional or space limitations inside the human body, required range of motions, safety, *etc*. An example of developing soft robots based on specific medical considerations and intended use is given in [143], proposing a soft robot for cardiac intervention.

4.2 Conclusions

Soft robots have numerous types, functionality, and degrees of freedom that make their classification complex, especially when soft medical robots are the study focus. In this article, soft robots were introduced by explaining the materials and fabrication methods to implicitly highlight the borders around the scope of the branch of robotics known as soft robotics. The continuum robot as the end-effector or mechanical manipulator of surgical robots was introduced. Many soft robots that are reviewed in this paper essentially share the topology and kinematics of the rigid continuum robot. The trends show research interest in developing soft robots for different robotic tasks including positioning, grasping, and force exertion. In the field of medical robots, trunk-like elastomeric soft robots play the main role in the exhibition of designs for the next generation of medical insertion tubes and surgical devices. Additionally, such systems have been employed as actuators for other medical robots such as wearable rehabilitation and assistive robots. The publication trends show continuous and intensive research and determination of the scientific society to improve the quality and performance of soft robots. It was discussed that advances in relevant technologies make the perspective of soft robots positive, inclusively in medical and surgical applications. However, for designing soft robots for each particular medical intended use, further biomedical requirements and considerations should be considered.

References:

[1] H. Abidi *et al.*, "Highly dexterous 2- module soft robot for intra- organ navigation in minimally invasive surgery," *The International Journal of Medical Robotics and Computer Assisted Surgery,* vol. 14, no. 1, p. e1875, 2018.

[2] A. Razjigaev *et al.*, "Optimal Vision-Based Orientation Steering Control for a 3D Printed Dexterous Snake-Like Manipulator to Assist Teleoperation," 2023.

[3] A. Brodie and N. Vasdev, "The future of robotic surgery," *The Annals of The Royal College of Surgeons of England,* vol. 100, no. Supplement 7, pp. 4-13, 2018.

[4] F. Cepolina and R. P. Razzoli, "An introductory review of robotically assisted surgical systems," *The International Journal of Medical Robotics and Computer Assisted Surgery,* vol. 18, no. 4, p. e2409, 2022.

[5] B. S. Peters, P. R. Armijo, C. Krause, S. A. Choudhury, and D. Oleynikov, "Review of emerging surgical robotic technology," *Surgical Endoscopy,* journal article vol. 32, no. 4, pp. 1636-1655, April 01 2018.

[6] A. Boese *et al.*, "Endoscopic imaging technology today," *Diagnostics* vol. 12, no. 5, p. 1262, 2022.

[7] B. Tondu and P. Lopez, "Modeling and control of McKibben artificial muscle robot actuators," *IEEE Control Systems Magazine,* vol. 20, no. 2, pp. 15-38, 2000.

[8] X. Wang, H. Kang, H. Zhou, W. Au, M. Y. Wang, and C. Chen, "Development and evaluation of a robust soft robotic gripper for apple harvesting," *Computers and Electronics in Agriculture,* vol. 204, p. 107552, 2023.

[9] W. Ji, G. He, B. Xu, H. Zhang, and X. Yu, "A New Picking Pattern of a Flexible Three-Fingered End-Effector for Apple Harvesting Robot," *Agriculture,* vol. 14, no. 1, p. 102, 2024.

[10] M. Sayahkarajy and A. A. Mohd Faudzi, "Design of a Mechatronic Interface with Compliant Manipulator for Robot Assisted Echocardiography," In *Journal of Physics Conference Series*, 2021, vol. 2107, no. 1, p. 012005.

[11] Y. Zhang and M. Lu, "A review of recent advancements in soft and flexible robots for medical applications," *The International Journal of Medical Robotics and Computer Assisted Surgery,* vol. 16, no. 3, p. e2096, 2020.

[12] Z. Yang, H. Yang, Y. Cao, Y. Cui, and L. Zhang, "Magnetically Actuated Continuum Medical Robots: A Review," *Advanced Intelligent Systems,* p. 2200416, 2023.

[13] W. Heng, S. Solomon, and W. Gao, "Flexible electronics and devices as human–machine interfaces for medical robotics," *Advanced Materials,* vol. 34, no. 16, p. 2107902, 2022.

[14] D. Rus and M. T. Tolley, "Design, fabrication and control of soft robots," *Nature,* vol. 521, no. 7553, p. 467, 2015.

[15] M. Sayahkarajy, "Mode shape analysis, modal linearization, and control of an elastic two-link manipulator based on the normal modes," *Applied Mathematical Modelling,* vol. 59, pp. 546-570, 2018.

[16] Y. L. Yap, S. L. Sing, and W. Y. Yeong, "A review of 3D printing processes and materials for soft robotics," *Rapid Prototyping Journal,* 2020.

[17] G. Stano and G. Percoco, "Additive manufacturing aimed to soft robots fabrication: A review," *Extreme Mechanics Letters,* vol. 42, p. 101079, 2021.

[18] R. Drury, V. Sencadas, and G. Alici, "3D Printed Linear Soft Multi-Mode Actuators Expanding Robotic Applications," *Soft Matter,* 2022.

[19] H. D. Mohammad *et al.*, "3D Printing of Small-Scale Soft Robots with Programmable

Magnetization," *Advanced Functional Materials,* vol. 33, no. 15, 2023.

[20] M. Y. Khalid, Z. U. Arif, A. Tariq, M. Hossain, K. A. Khan, and R. Umer, "3D printing of magneto-active smart materials for advanced actuators and soft robotics applications," *European Polymer Journal,* p. 112718, 2024.

[21] D. Rus and M. T. Tolley, "Design, fabrication and control of origami robots," *Nature Reviews Materials,* p. 1, 2018.

[22] J. Liu, G. Ma, Z. Ma, and S. Zuo, "Origami-inspired soft-rigid hybrid contraction actuator and Its application in pipe-crawling robot," *Smart Materials and Structures,* 2023.

[23] V. Agarwal and K. Wang, "On the nonlinear dynamics of a Kresling-pattern origami under harmonic force excitation," *Extreme Mechanics Letters,* p. 101653, 2022.

[24] H. Zhang and J. Paik, "Kirigami Design and Modeling for Strong, Lightweight Metamaterials," *Advanced Functional Materials,* vol. 32, no. 21, p. 2107401, 2022.

[25] K. Zhang, Y. Fan, S. Shen, X. Yang, and T. Li, "Tunable Folding Assembly Strategy for Soft Pneumatic Actuators," *Soft Robotics,* vol. 10, no. 6, pp. 1099-1114, 2023.

[26] D.-M. Rusu, S.-D. Mândru, C.-M. Biriș, O.-L. Petrașcu, F. Morariu, and A. Ianosi-Andreeva-Dimitrova, "Soft robotics: A systematic review and bibliometric analysis," *Micromachines,* vol. 14, no. 2, p. 359, 2023.

[27] J. Fang *et al.*, "Novel Accordion-Inspired Foldable Pneumatic Actuators for Knee Assistive Devices," *Soft Robotics,* 2019.

[28] J. Hwee, A. Lewis, A. Raines, and B. Hannaford, "Kinematic Modeling of a Soft Everting Robot from Inflated Beam Theory," In*2023 IEEE International Conference on Soft Robotics (RoboSoft)*, 2023, pp. 1-6: IEEE.

[29] P. F *et al.*, "3D Kinematics and Quasi-Statics of a Growing Robot Eversion," In *2023 IEEE International Conference on Soft Robotics (RoboSoft)*, 2023, pp. 1-6.

[30] A. Raines, A. Lewis, J. Hwee, and B. Hannaford, "Inferring Environmental Interactions of Soft Everting Robots From Acoustic Signals," In*2023 IEEE International Conference on Soft Robotics (RoboSoft)*, 2023, pp. 1-6.

[31] K. Eken, N. Gravish, and M. T. Tolley, "Continuous Skin Eversion Enables an Untethered Soft Robot to Burrow in Granular Media," In*2023 IEEE International Conference on Soft Robotics (RoboSoft)*, 2023, pp. 1-6: IEEE.

[32] D. Drotman, M. Ishida, S. Jadhav, and M. T. Tolley, "Application-Driven Design of Soft, 3D Printed, Pneumatic Actuators with Bellows," *IEEE/ASME Transactions on Mechatronics,* 2018.

[33] J. H. Park *et al.*, "Cooperative antagonistic mechanism driven by bidirectional pneumatic artificial muscles for soft robotic joints," *Mechatronics,* vol. 97, p. 103099, 2024.

[34] A. Huang *et al.*, "Foam-Embedded Soft Robotic Joint With Inverse Kinematic Modeling by Iterative Self-Improving Learning," *IEEE Robotics and Automation Letters,* 2024.

[35] Y. Hwang, O. H. Paydar, and R. N. Candler, "Pneumatic microfinger with balloon fins for linear motion using 3D printed molds," *Sensors and Actuators A: Physical,* vol. 234, pp. 65-71, 2015.

[36] C. Xiang, Z. Li, X. Luo, C. Huang, Y. Guan, and Structures, "Soft electroadhesive grippers with variable stiffness and deflection motion capabilities," *Smart Materials and Structures,* 2023.

[37] A. D. Marchese, R. K. Katzschmann, and D. Rus, "A recipe for soft fluidic elastomer robots," *Soft Robotics,* vol. 2, no. 1, pp. 7-25, 2015.

[38] J. Shi, W. Gaozhang, and H. Wurdemann, "Design and Characterisation of Cross-sectional Geometries for Soft Robotic Manipulators with Fibre-reinforced Chambers," In *2022 IEEE 5th International Conference on Soft Robotics (RoboSoft)*, 2022, vol. 2022: IEEE.

[39] S. Kokubu, P. E. T. Vinocour, and W. Yu, "Development and evaluation of fiber reinforced modular soft actuators and an individualized soft rehabilitation glove," *Robotics and Autonomous Systems,* vol. 171, p. 104571, 2024.

[40] M. A. Khan, S. Shaik, M. H. Tariq, and T. Kamal, "McKibben Pneumatic Artificial Muscle Robot Actuators-A Review," In *2023 International Conference on Robotics and Automation in Industry (ICRAI)*, 2023, pp. 1-6: IEEE.

[41] B. Kalita, A. Leonessa, and S. K. Dwivedy, "A review on the development of pneumatic artificial muscle actuators: Force model and

application," In*Actuators*, 2022, vol. 11, no. 10, p. 288: MDPI.

[42] S. Koizumi, S. Kurumaya, H. Nabae, G. Endo, and K. Suzumori, "Braiding Thin McKibben Muscles to Enhance Their Contracting Abilities," *IEEE Robotics and Automation Letters,* vol. 3, no. 4, pp. 3240-3246, 2018.

[43] J. Yi, X. Chen, C. Song, and Z. Wang, "Fiber-reinforced origamic robotic actuator," *Soft Robotics,* vol. 5, no. 1, pp. 81-92, 2018.

[44] J. Li, S. Wu, W. Zhang, K. Ma, and G. Jin, "3D printing of silicone elastomers for soft actuators," In*Actuators*, 2022, vol. 11, no. 7, p. 200: MDPI.

[45] D. Gonzalez, J. Garcia, R. M. Voyles, R. A. Nawrocki, and B. Newell, "Characterization of 3D printed pneumatic soft actuator," *Sensors and Actuators A: Physical,* vol. 334, p. 113337, 2022.

[46] W. Zhou and Y. Li, "Modeling and Analysis of Soft Pneumatic Actuator with Symmetrical Chambers Used for Bionic Robotic Fish," *Soft Robotics,* 2019.

[47] G. Singh and G. Krishnan, "Designing Fiber-Reinforced Soft Actuators for Planar Curvilinear Shape Matching," *Soft Robotics,* 2019.

[48] H. Kim *et al.*, "Shape morphing smart 3D actuator materials for micro soft robot," *Materials Today,* 2020.

[49] J. Wang and A. Chortos, "Control Strategies for Soft Robot Systems," *Advanced Intelligent Systems,* p. 2100165, 2022.

[50] W. Fan, J. Wang, Z. Zhang, G. Chen, and H. Wang, "Vacuum-Driven Parallel Continuum Robots With Self-Sensing Origami Linkages," *IEEE/ASME Transactions on Mechatronics,* 2024.

[51] Z. Yu-hao, Z. Hui, and T. Dai-bin, "Review of Fluid Driving Methods in Soft Robot," *Chinese Hydraulics Pneumatics,* vol. 45, no. 4, p. 135, 2021.

[52] S. Zaidi, M. Maselli, C. Laschi, and M. Cianchetti, "Actuation Technologies for Soft Robot Grippers and Manipulators: A Review," *Current Robotics Reports,* pp. 1-15, 2021.

[53] C. Ahn, X. Liang, and S. Cai, "Inhomogeneous stretch induced patterning of molecular orientation in liquid crystal elastomers," *Extreme Mechanics Letters,* vol. 5, pp. 30-36, 2015.

[54] H. K. Bisoyi, A. M. Urbas, and Q. Li, "Soft materials driven by photothermal effect and their applications," *Advanced Optical Materials,* vol. 6, no. 15, p. 1800458, 2018.

[55] Q. He, Z. Wang, Y. Wang, A. Minori, M. T. Tolley, and S. Cai, "Electrically controlled liquid crystal elastomer–based soft tubular actuator with multimodal actuation," *Science Advances,* vol. 5, no. 10, p. eaax5746, 2019.

[56] T. Ren, Y. Li, M. Xu, Y. Li, C. Xiong, and Y. Chen, "A Novel Tendon-Driven Soft Actuator with Self-Pumping Property," *Soft robotics,* 2019.

[57] W. R. Wockenfu, L. Weisheit, V. Brandt, and W.-G. Drossel, "Design, Modeling and Validation of a Tendon-driven Soft Continuum Robot for Planar Motion based on Variable Stiffness Structures," *IEEE Robotics Automation Letters,* 2022.

[58] X. Zeng and H.-J. Su, "A High Performance Pneumatically Actuated Soft Gripper Based on Layer Jamming," *Journal of Mechanisms and Robotics,* pp. 1-17, 2022.

[59] K. Mcdonald, L. Kinnicutt, A. M. Moran, and T. Ranzani, "Modulation of Magnetorheological Fluid Flow in Soft Robots Using Electropermanent Magnets," *IEEE Robotics and Automation Letters,* 2022.

[60] S. G. Fitzgerald, G. W. Delaney, and D. Howard, "A Review of Jamming Actuation in Soft Robotics," In*Actuators*, 2020, vol. 9, no. 4, p. 104: Multidisciplinary Digital Publishing Institute.

[61] Y. Yang, H. Zhu, J. Liu, Z. Wei, Y. Li, and J. Zhou, "A Novel Variable Stiffness and Tunable Bending Shape Soft Robotic Finger based on Thermoresponsive Polymers," *IEEE Transactions on Instrumentation Measurement,* 2023.

[62] L. Zhang, Q. Huang, W. Wang, and K. Cai, "Design and Characterization of a Soft Vacuum-Actuated Rotary Actuator," *Journal of Mechanisms and Robotics,* vol. 12, no. 1, 2020.

[63] Q. Guan *et al.*, "Multifunctional Soft Stackable Robots by Netting–Rolling–Splicing Pneumatic Artificial Muscles," *Soft Robotics,* 2023.

[64] A. Firouzeh, M. Salerno, and J. Paik, "Soft pneumatic actuator with adjustable stiffness layers for multi-dof actuation," In*Intelligent Robots and Systems (IROS), 2015 IEEE/RSJ International Conference on*, 2015, pp. 1117-1124: IEEE.

[65] W. Hu and G. Alici, "Bioinspired three-dimensional-printed helical soft pneumatic

actuators and their characterization," *Soft Robotics,* vol. 7, no. 3, pp. 267-282, 2020.

[66] M. W. Hannan and I. D. Walker, "Kinematics and the implementation of an elephant's trunk manipulator and other continuum style robots," *Journal of robotic systems,* vol. 20, no. 2, pp. 45-63, 2003.

[67] M. M. Dalvand, S. Nahavandi, and R. D. Howe, "An Analytical Loading Model for n-Tendon Continuum Robots," *IEEE Transactions on Robotics,* no. 99, pp. 1-11, 2018.

[68] C. Armanini, F. Boyer, A. T. Mathew, C. Duriez, and F. Renda, "Soft Robots Modeling: A Structured Overview," *IEEE Transactions on Robotics,* 2023.

[69] Z. Mitros, S. H. Sadati, S. Nousias, L. Da Cruz, and C. Bergeles, "Design and Quasistatic Modelling of Hybrid Continuum Multi-Arm Robots," 2022.

[70] Z. Chen, X. Liang, T. Wu, T. Yin, Y. Xiang, and S. Qu, "Pneumatically Actuated Soft Robotic Arm for Adaptable Grasping," *Acta Mechanica Solida Sinica,* 2018/08/29 2018.

[71] A. Yin, H. C. Lin, J. Thelen, B. Mahner, and T. Ranzani, "Combining Locomotion and Grasping Functionalities in Soft Robots," *Advanced Intelligent Systems,* 2022.

[72] H. Ji, Y. Lan, S. Nie, L. Huo, F. Yin, and R. Hong, "Development of an Anthropomorphic Soft Manipulator with Rigid-Flexible Coupling for Underwater Adaptive Grasping," *Soft Robotics,* 2023.

[73] F. Stroppa, "Design optimizer for planar soft-growing robot manipulators," *Engineering Applications of Artificial Intelligence,* vol. 130, p. 107693, 2024.

[74] H. Su *et al.*, "Pneumatic soft robots: Challenges and benefits," In*Actuators*, 2022, vol. 11, no. 3, p. 92: MDPI.

[75] Y. Ansari, M. Manti, E. Falotico, M. Cianchetti, and C. Laschi, "Multiobjective optimization for stiffness and position control in a soft robot arm module," *IEEE Robotics and Automation Letters,* vol. 3, no. 1, pp. 108-115, 2018.

[76] W. Dou, G. Zhong, J. Cao, Z. Shi, B. Peng, and L. Jiang, "Soft robotic manipulators: Designs, actuation, stiffness tuning, and sensing," *Advanced Materials Technologies,* vol. 6, no. 9, p. 2100018, 2021.

[77] L. Li *et al.*, "Stiffness-Tunable Soft Gripper with Soft-Rigid Hybrid Actuation for Versatile Manipulations," *Soft Robotics,* 2022.

[78] L. Wang *et al.*, "Controllable and reversible tuning of material rigidity for robot applications," *Materials Today,* 2018.

[79] N. P. Bira, P. Dhagat, J. Davidson, and Structures, "Tuning the grasping strength of soft actuators with magnetic elastomer fingertips," *Smart Materials and Structures,* 2022.

[80] Y. Zhao and Y. Wang, "A Palm-Shape Variable-Stiffness Gripper based on 3D-Printed Fabric Jamming," *IEEE Robotics and Automation Letters,* 2023.

[81] Y. Piskarev *et al.*, "A Variable Stiffness Magnetic Catheter Made of a Conductive Phase- Change Polymer for Minimally Invasive Surgery," *Advanced Functional Materials,* p. 2107662, 2022.

[82] S. Yoshida, Y. Morimoto, L. Zheng, H. Onoe, and S. Takeuchi, "Multipoint Bending and Shape Retention of a Pneumatic Bending Actuator by a Variable Stiffness Endoskeleton," *Soft robotics,* 2018.

[83] G. Fantoni *et al.*, "Grasping devices and methods in automated production processes," *CIRP Annals-Manufacturing Technology,* vol. 63, no. 2, pp. 679-701, 2014.

[84] B. S. Homberg, R. K. Katzschmann, M. R. Dogar, and D. Rus, "Robust proprioceptive grasping with a soft robot hand," *Autonomous Robots,* pp. 1-16, 2018.

[85] H. M. Le, L. Cao, T. N. Do, and S. J. Phee, "Design and modelling of a variable stiffness manipulator for surgical robots," *Mechatronics,* vol. 53, pp. 109-123, 2018/08/01/ 2018.

[86] L. Zhao and S. K. Gupta, "Design, Manufacturing, and Characterization of a Pneumatically-Actuated Soft Hand," no. 51371, p. V003T02A004, 2018.

[87] H. Zhang, A. S. Kumar, F. Chen, J. Y. Fuh, and M. Y. Wang, "Topology Optimized Multimaterial Soft Fingers for Applications on Grippers, Rehabilitation and Artificial Hands," *IEEE/ASME Transactions on Mechatronics,* 2018.

[88] M. P. Bendsøe and O. Sigmund, "Topology optimization by distribution of isotropic material," In*Topology Optimization*: Springer, 2004, pp. 1-69.

[89] B. T. Phillips *et al.*, "A Dexterous, Glove-Based Teleoperable Low-Power Soft Robotic Arm for Delicate Deep-Sea Biological Exploration," *Scientific reports,* vol. 8, no. 1, p. 14779, 2018.

[90] H. Huang, L. Wu, J. Lin, B. Fang, and F. Sun, "A novel mode controllable hybrid valve pressure control method for soft robotic gripper," *International Journal of Advanced Robotic Systems,* 2018.

[91] E. Navas, R. Fernández, D. Sepúlveda, M. Armada, and P. Gonzalez-de-Santos, "Soft Grippers for Automatic Crop Harvesting: A Review," *Sensors and Actuators A: Physical,* vol. 21, no. 8, p. 2689, 2021.

[92] T. Jiralerspong, K. H. Heung, R. K. Tong, and Z. Li, "A Novel Soft Robotic Glove for Daily Life Assistance," In*2018 7th IEEE International Conference on Biomedical Robotics and Biomechatronics (Biorob)*, 2018, pp. 671-676: IEEE.

[93] W. Park, S. Seo, and J. Bae, "A Hybrid Gripper with Soft Material and Rigid Structures," *IEEE Robotics and Automation Letters,* 2018.

[94] C. Rose and M. O'Malley, "A Hybrid Rigid-Soft Hand Exoskeleton to Assist Functional Dexterity," *IEEE Robotics and Automation Letters,* 2018.

[95] X. Guo *et al.*, "Encoded sewing soft textile robots," *Science Advances,* vol. 10, no. 1, p. eadk3855, 2024.

[96] J. Nassour and F. Hamker, "Enfolded Textile Actuator for Soft Wearable Robots," 2022.

[97] G. Gerboni, A. Diodato, G. Ciuti, M. Cianchetti, and A. Menciassi, "Feedback control of soft robot actuators via commercial flex bend sensors," *IEEE/ASME Transactions on Mechatronics,* vol. 22, no. 4, pp. 1881-1888, 2017.

[98] H. Yang, M. Xu, W. Li, and S. Zhang, "Design and Implementation of a Soft Robotic Arm Driven by SMA Coils," *IEEE Transactions on Industrial Electronics,* 2018.

[99] T. Wang, Y. Zhang, and Z. Chen, "Design and Verification of Model-based Nonlinear Controller for Fluidic Soft Actuators," In*2018 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM)*, 2018, pp. 1178-1183: IEEE.

[100] R. T. Farouki, *Pythagorean—hodograph Curves*. Springer, 2008.

[101] I. Singh, Y. Amara, A. Melingui, P. Mani Pathak, and R. Merzouki, "Modeling of Continuum Manipulators Using Pythagorean Hodograph Curves," *Soft robotics,* 2018.

[102] D. Kim *et al.*, "Review of machine learning methods in soft robotics," *Plos one,* vol. 16, no. 2, p. e0246102, 2021.

[103] D. Bruder, X. Fu, R. B. Gillespie, C. D. Remy, and R. Vasudevan, "Data-driven control of soft robots using Koopman operator theory," *IEEE Transactions on Robotics,* vol. 37, no. 3, pp. 948-961, 2020.

[104] D. Papageorgiou, G. Þ. Sigurðardóttir, E. Falotico, and S. Tolu, "Sliding-mode control of a soft robot based on data-driven sparse identification," *Control Engineering Practice,* vol. 144, p. 105836, 2024.

[105] S. I. Lee, E. J. Song, Y. I. Yun, H. Moon, H. R. Choi, and J. C. Koo, "Soft pneumatic actuator workspace augmentation with synthesis of simplified analytical and numerical subcomponent models," *Sensors and Actuators A: Physical,* vol. 365, p. 114814, 2024.

[106] M. A. Robertson, H. Sadeghi, J. M. Florez, and J. Paik, "Soft pneumatic actuator fascicles for high force and reliability," *Soft robotics,* vol. 4, no. 1, pp. 23-32, 2017.

[107] Y. Sun, Y. S. Song, and J. Paik, "Characterization of silicone rubber based soft pneumatic actuators," In*Intelligent Robots and Systems (IROS), 2013 IEEE/RSJ International Conference on*, 2013, pp. 4446-4453: Ieee.

[108] J. Surentu, G. J. Tuijthof, and J. L. Herder, "Optimized artificial muscles for an inherently safe robotic arm," In*Rehabilitation Robotics, 2007. ICORR 2007. IEEE 10th International Conference on*, 2007, pp. 1070-1076: IEEE.

[109] R. Su, Y. Tian, M. Du, and C. C. Wang, "Optimizing out-of-plane stiffness for soft grippers," *IEEE Robotics and Automation Letters,* 2022.

[110] J. Pardomuan, N. Takahashi, and H. Koike, "ASTRE: Prototyping Technique for Modular Soft Robots with Variable Stiffness," *IEEE Access,* 2022.

[111] Y. Park, J. Kang, and Y. Na, "Reconfigurable Shape Morphing With Origami-Inspired Pneumatic Blocks," *IEEE Robotics and Automation Letters,* vol. 7, no. 4, pp. 9453-9460, 2022.

[112] F. Daerden and D. Lefeber, "Pneumatic artificial muscles: actuators for robotics and automation," *European journal of mechanical and environmental engineering,* vol. 47, no. 1, pp. 11-21, 2002.

[113] V. Sanchez *et al.*, "3D Knitting for Pneumatic Soft Robotics," *Advanced Functional Materials,* p. 2212541, 2023.

[114] M. De Volder, A. Moers, and D. Reynaerts, "Fabrication and control of miniature McKibben actuators," *Sensors and Actuators A: Physical,* vol. 166, no. 1, pp. 111-116, 2011.

[115] K. Suzumori, S. Seita, S. Wakimoto, and K. Kouno, "Mckibben artificial muscle," ed: Google Patents, 2018.

[116] G. K. Klute, J. M. Czerniecki, and B. Hannaford, "McKibben artificial muscles: pneumatic actuators with biomechanical intelligence," In*Advanced Intelligent Mechatronics, 1999. Proceedings. 1999 IEEE/ASME International Conference on*, 1999, pp. 221-226: IEEE.

[117] T. Nakamura, N. Saga, and K. Yaegashi, "Development of a pneumatic artificial muscle based on biomechanical characteristics," In*Industrial Technology, 2003 IEEE International Conference on*, 2003, vol. 2, pp. 729-734: IEEE.

[118] A. A. M. Faudzi, G. Endo, S. Kurumaya, and K. Suzumori, "Long-legged hexapod giacometti robot using thin soft McKibben actuator," *IEEE Robotics and Automation Letters,* vol. 3, no. 1, pp. 100-107, 2018.

[119] A. A. M. Faudzi, J. Ooga, T. Goto, M. Takeichi, and K. Suzumori, "Index finger of a human-like robotic hand using thin soft muscles," *IEEE Robotics and Automation Letters,* vol. 3, no. 1, pp. 92-99, 2018.

[120] Y. Peng, H. Nabae, Y. Funabora, K. J. S. Suzumori, and A. A. Physical, "Peristaltic transporting device inspired by large intestine structure," vol. 365, p. 114840, 2024.

[121] B. A. Baydere, S. K. Talas, and E. Samur, "A novel highly-extensible 2-DOF pneumatic actuator for soft robotic applications," *Sensors and Actuators A: Physical,* vol. 281, pp. 84-94, 2018.

[122] B. Tondu, "Modelling of the McKibben artificial muscle: A review," *Journal of Intelligent Material Systems and Structures,* vol. 23, no. 3, pp. 225-253, 2012.

[123] C.-P. Chou and B. Hannaford, "Measurement and modeling of McKibben pneumatic artificial muscles," *IEEE Transactions on robotics and automation,* vol. 12, no. 1, pp. 90-102, 1996.

[124] D. Reynolds, D. Repperger, C. Phillips, and G. Bandry, "Modeling the dynamic characteristics of pneumatic muscle," *Annals of biomedical engineering,* vol. 31, no. 3, pp. 310-317, 2003.

[125] B.-S. Kang, C. S. Kothera, B. K. Woods, and N. M. Wereley, "Dynamic modeling of Mckibben pneumatic artificial muscles for antagonistic actuation," In*Robotics and Automation, 2009. ICRA'09. IEEE International Conference on*, 2009, pp. 182-187: IEEE.

[126] B. Tondu and P. Lopez, "Modeling and control of McKibben artificial muscle robot actuators," *IEEE control systems,* vol. 20, no. 2, pp. 15-38, 2000.

[127] G. K. Klute and B. Hannaford, "Fatigue characteristics of McKibben artificial muscle actuators," In*Intelligent Robots and Systems, 1998. Proceedings., 1998 IEEE/RSJ International Conference on*, 1998, vol. 3, pp. 1776-1781: IEEE.

[128] M. Meller, B. Kogan, M. Bryant, and E. Garcia, "Model-based feedforward and cascade control of hydraulic McKibben muscles," *Sensors and Actuators A: Physical,* vol. 275, pp. 88-98, 2018.

[129] D. Sangian, S. Naficy, G. M. Spinks, and B. Tondu, "The effect of geometry and material properties on the performance of a small hydraulic McKibben muscle system," *Sensors and Actuators A: Physical,* vol. 234, pp. 150-157, 2015.

[130] Y. Yamamoto, S. Wakimoto, T. Kanda, and D. Yamaguchi, "A Soft Robot Arm with Flexible Sensors for Master-Slave Operation," *Engineering Proceedings*.

[131] F. Qi, F. Ju, D. Bai, Y. Wang, and B. Chen, "Motion modelling and error compensation of a cable-driven continuum robot for applications to minimally invasive surgery," *The International Journal of Medical Robotics and Computer Assisted Surgery,* vol. 0, no. 0, p. e1932, 2018.

[132] S. J. Phee, S. C. Low, P. Dario, and A. Menciassi, "Tendon sheath analysis for estimation of distal end force and elongation for sensorless distal end," *Robotica,* vol. 28, no. 7, pp. 1073-1082, 2010.

[133] L. S. Chiang, P. S. Jay, P. Valdastri, A. Menciassi, and P. Dario, "Tendon sheath analysis for estimation of distal end force and elongation," In*Advanced Intelligent Mechatronics, 2009. AIM 2009. IEEE/ASME International Conference on*, 2009, pp. 332-337: IEEE.

[134] G. Ateş, R. Majani, and M. İ. C. Dede, "Design of a Teleoperation Scheme with a Wearable Master for Minimally Invasive Surgery," In *New Trends in Medical and Service Robotics*: Springer, 2019, pp. 45-53.

[135] C. Pahl, H. Ebelt, M. Sayahkarajy, E. Supriyanto, and A. Soesanto, "Towards Robot-Assisted Echocardiographic Monitoring in Catheterization Laboratories," *Journal of medical systems,* vol. 41, no. 10, p. 148, 2017.

[136] Y.-T. Liao, C.-Y. Chen, J.-Y. Yen, M.-C. Ho, and Y.-Y. Chen, "Comparison of the Control Designs of an Human Co-Working Endoscope Holder," In *2018 26th Mediterranean Conference on Control and Automation (MED)*, 2018, pp. 1-9: IEEE.

[137] N. Simaan, R. M. Yasin, and L. Wang, "Medical Technologies and Challenges of Robot-Assisted Minimally Invasive Intervention and Diagnostics," *Annual Review of Control, Robotics, and Autonomous Systems,* vol. 1, pp. 465-490, 2018.

[138] L. Paternò, G. Tortora, and A. Menciassi, "Hybrid Soft–Rigid Actuators for Minimally Invasive Surgery," *Soft robotics,* 2018.

[139] M. W. Gifari, H. Naghibi, S. Stramigioli, and M. Abayazid, "A review on recent advances in soft surgical robots for endoscopic applications," *The International Journal of Medical Robotics and Computer Assisted Surgery,* vol. 15, no. 5, p. e2010, 2019.

[140] A. B. Dawood *et al.*, "Fusing Dexterity and Perception for Soft Robot-Assisted Minimally Invasive Surgery: What We Learnt from STIFF-FLOP," *Applied Sciences,* vol. 11, no. 14, p. 6586, 2021.

[141] Y. Zhang and M. Lu, "A review of recent advancements in soft and flexible robots for medical applications," *The International Journal of Computer Assisted Radiology and Surgery,* vol. 16, no. 3, p. e2096, 2020.

[142] M. McCandless, A. Gerald, A. Carroll, H. Aihara, and S. J. I. r. Russo, "A soft robotic sleeve for safer colonoscopy procedures," *IEEE robotics and automation letters,* vol. 6, no. 3, pp. 5292-5299, 2021.

[143] J. Rogatinsky *et al.*, "A multifunctional soft robot for cardiac interventions," *Science Advances,* vol. 9, no. 43, p. eadi5559, 2023.

[144] A. Alian *et al.*, "Current Engineering Developments for Robotic Systems in Flexible Endoscopy," *Techniques and Innovations in Gastrointestinal Endoscopy,* vol. 25, no. 1, pp. 67-81, 2023.

[145] T. Ashuri, A. Armani, R. Jalilzadeh Hamidi, T. Reasnor, S. Ahmadi, and K. Iqbal, "Biomedical soft robots: current status and perspective," *Biomedical Engineering Letters,* vol. 10, pp. 369-385, 2020.

[146] Z. Zhang, A. D. Calderon, X. Huang, and A. Huang, "Research Status and Prospect of Finger Rehabilitation Machinery," *Medical Devices: Evidence Research,* pp. 1-22, 2024.

[147] M. Runciman, A. Darzi, and G. P. Mylonas, "Soft robotics in minimally invasive surgery," *Soft robotics,* vol. 6, no. 4, pp. 423-443, 2019.

[148] J. Zhu *et al.*, "Intelligent soft surgical robots for next- generation minimally invasive surgery," *Advanced Intelligent Systems,* vol. 3, no. 5, p. 2100011, 2021.

[149] B. Zhang, P. Yang, X. Gu, and H. Liao, "Laser Endoscopic Manipulator Using Spring-Reinforced Multi-DoF Soft Actuator," *IEEE Robotics and Automation Letters,* vol. 6, no. 4, pp. 7736-7743, 2021.

[150] G. Decroly, P. Lambert, A. Delchambre, and AI, "A soft pneumatic two-degree-of-freedom actuator for endoscopy," *Frontiers in Robotics and AI,* vol. 8, p. 768236, 2021.

[151] K. Ashwin and A. Ghosal, "A soft-robotic end-effector for independently actuating endoscopic catheters," *Journal of Mechanisms and Robotics* vol. 11, no. 6, p. 061004, 2019.

[152] M. T. Thai *et al.*, "Advanced soft robotic system for in situ 3D bioprinting and endoscopic surgery," *Advanced Science,* vol. 10, no. 12, p. 2205656, 2023.

[153] M. Chauhan *et al.*, "An origami-based soft robotic actuator for upper gastrointestinal endoscopic applications," *Frontiers in Robotics and AI,* p. 119, 2021.

[154] Q. Jacquemin, Q. Sun, D. Thuau, E. Monteiro, S. Tence-Girault, and N. Mechbal, "Design of a new electroactive polymer based continuum actuator for endoscopic surgical robots," In *2020 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2020, pp. 3208-3215: IEEE.

[155] H. Kim, J. M. You, K. U. Kyung, and D. S. Kwon, "Endoscopic Surgery Robot that Facilitates Insertion of the Curved Colon and Ensures Positional Stability Against External Forces: K- COLON," *The International*

Journal of Medical Robotics and Computer Assisted Surgery, p. e2493, 2022.

[156] L. Blanc, A. Delchambre, and P. Lambert, "Flexible medical devices: review of controllable stiffness solutions," *Actuators*, 2017, vol. 6, no. 3, p. 23: Multidisciplinary Digital Publishing Institute.

[157] D. Shen, Q. Zhang, Y. Han, C. Tu, and X. Wang, "Design and Development of a Continuum Robot with Switching-Stiffness," *Soft Robotics,* 2023.

[158] M. Pan *et al.*, "Soft actuators and robotic devices for rehabilitation and assistance," *Advanced Intelligent Systems,* vol. 4, no. 4, p. 2100140, 2022.

[159] J. Wang, Y. Fei, and W. Chen, "Integration, Sensing, and Control of a Modular Soft-Rigid Pneumatic Lower Limb Exoskeleton," *Soft robotics,* 2019.

[160] P. Tran *et al.*, "FLEXotendon Glove-III: Voice-Controlled Soft Robotic Hand Exoskeleton With Novel Fabrication Method and Admittance Grasping Control," *IEEE/ASME Transactions on Mechatronics,* 2022.

[161] C.-Y. Chu and R. M. Patterson, "Soft robotic devices for hand rehabilitation and assistance: a narrative review," *Journal of NeuroEngineering and Rehabilitation,* journal article vol. 15, no. 1, p. 9, February 17 2018.

[162] S. Kokubu, R. Nishimura, and W. Yu, "Deriving Design Rules for Personalization of Soft Rehabilitation Gloves," *IEEE Access,* 2024.

[163] D. Qi, K. Zhang, G. Tian, B. Jiang, and Y. Huang, "Stretchable electronics based on PDMS substrates," *Advanced Materials,* vol. 33, no. 6, p. 2003155, 2021.

[164] E. Liu, Z. Cai, Y. Ye, M. Zhou, H. Liao, and Y. Yi, "An Overview of Flexible Sensors: Development, Application, and Challenges," *Sensors,* vol. 23, no. 2, p. 817, 2023.

[165] X. Ding and J. M. Moran-Mirabal, "Efficient Multi-Material Structured Thin Film Transfer to Elastomers for Stretchable Electronic Devices," *Micromachines,* vol. 13, no. 2, p. 334, 2022.

[166] L. Chen, X. Chang, H. Wang, J. Chen, and Y. Zhu, "Stretchable and Transparent Multimodal Electronic-Skin Sensors in Detecting Strain, Temperature, and Humidity," *Nano Energy,* p. 107077, 2022.

[167] W. Kong *et al.*, "An ultra-low hysteresis, self-healing and stretchable conductor based on dynamic disulfide covalent adaptable networks," *Journal of Materials Chemistry,* 2022.

[168] Q. Huang and Y. Zhu, "Printing conductive nanomaterials for flexible and stretchable electronics: A review of materials, processes, and applications," *Advanced Materials Technologies,* vol. 4, no. 5, p. 1800546, 2019.

[169] B. Lee *et al.*, "Omnidirectional printing of elastic conductors for three-dimensional stretchable electronics," *Nature Electronics,* pp. 1-12, 2023.

[170] C. Okutani, T. Yokota, H. Miyazako, and T. Someya, "3D Printed Spring- Type Electronics with Liquid Metals for Highly Stretchable Conductors and Inductive Strain/Pressure Sensors," *Advanced Materials Technologies,* p. 2101657, 2022.

[171] Y. Jo *et al.*, "Printable Self-Activated Liquid Metal Stretchable Conductors from Polyvinylpyrrolidone-Functionalized Eutectic Gallium Indium Composites," *ACS Applied Materials,* 2022.

[172] P. Karipoth *et al.*, "Aerosol Jet Printing of Strain Sensors for Soft Robotics," *Advanced Engineering Materials,* vol. 26, no. 1, p. 2301275, 2024.

[173] N. Lu and S. Yang, "Mechanics for stretchable sensors," *Current Opinion in Solid State and Materials Science,* vol. 19, no. 3, pp. 149-159, 2015.

[174] Q. Ji, J. Jansson, M. Sjöberg, X. V. Wang, L. Wang, and L. Feng, "Design and calibration of 3D printed soft deformation sensors for soft actuator control," *Mechatronics,* vol. 92, p. 102980, 2023.

[175] S. Utrera-Barrios *et al.*, "Unlocking the potential of self-healing and recyclable ionic elastomers for soft robotics applications," *Materials Horizons,* 2024.

[176] S. I. Rich, R. J. Wood, and C. Majidi, "Untethered soft robotics," *Nature Electronics,* vol. 1, no. 2, p. 102, 2018.

[177] J. Davies *et al.*, "Bio-SHARPE: Bioinspired Soft and High Aspect Ratio Pumping Element for Robotic and Medical Applications," *Soft Robotics,* 2023.

[178] N. Wettels, V. J. Santos, R. S. Johansson, and G. E. Loeb, "Biomimetic tactile sensor array," *Advanced Robotics,* vol. 22, no. 8, pp. 829-849, 2008.

[179] N. Wettels, A. R. Parnandi, J.-H. Moon, G. E. Loeb, and G. S. Sukhatme, "Grip control using biomimetic tactile sensing systems,"

IEEE/ASME Transactions On Mechatronics, vol. 14, no. 6, pp. 718-723, 2009.

[180] Z. Lu and H. Yu, "GTac-Hand: A Robotic Hand With Integrated Tactile Sensing and Extrinsic Contact Sensing Capabilities," *IEEE/ASME Transactions on Mechatronics,* 2023.

[181] D. Balamurugan *et al.*, "Texture Discrimination using a Soft Biomimetic Finger for Prosthetic Applications," In *2019 IEEE 16th International Conference on Rehabilitation Robotics (ICORR)*, 2019, pp. 380-385: IEEE.

[182] Z. Song *et al.*, "A flexible triboelectric tactile sensor for simultaneous material and texture recognition," *Nano Energy,* vol. 93, p. 106798, 2022.

[183] S. Terrile, A. López, and A. Barrientos, "Use of Finite Elements in the Training of a Neural Network for the Modeling of a Soft Robot," *Biomimetics,* vol. 8, no. 1, p. 56, 2023.

[184] W. Xin, F. Zhu, P. Wang, Z. Xie, Z. Tang, and C. Laschi, "Electrical impedance tomographic shape sensing for soft robots," *IEEE Robotics and Automation Letters,* vol. 8, no. 3, pp. 1555-1562, 2023.

[185] P. Preechayasomboon and E. Rombokas, "Sensuator: A hybrid sensor–actuator approach to soft robotic proprioception using recurrent neural networks," *Actuators*, 2021, vol. 10, no. 2, p. 30: MDPI.

[186] Z. Chen *et al.*, "Data Models Applied to Soft Robot Modeling and Control: A Review," *arXiv preprint arXiv:.12137,* 2023.

[187] T. Preller *et al.*, "Particle-reinforced and functionalized hydrogels for SpineMan, a soft robotics application," *Journal of Materials Science,* pp. 1-13, 2021.

[188] R. Chellattoan and G. Lubineau, "A Stretchable Fiber with Tunable Stiffness for Programmable Shape Change of Soft Robots," *Soft Robotics,* 2022.

[189] P. Schegg and C. Duriez, "Review on generic methods for mechanical modeling, simulation and control of soft robots," *Plos one,* vol. 17, no. 1, p. e0251059, 2022.

[190] A. Heiden *et al.*, "3D printing of resilient biogels for omnidirectional and exteroceptive soft actuators," *Science Robotics,* vol. 7, no. 63, p. eabk2119, 2022.

[191] W. Sun *et al.*, "Biodegradable, Sustainable Hydrogel Actuators with Shape and Stiffness Morphing Capabilities via Embedded 3D Printing," *Advanced Functional Materials,* p. 2303659, 2023.

[192] M. A. Bell, K. P. Becker, and R. J. Wood, "Injection Molding of Soft Robots," *Advanced Materials Technologies,* vol. 7, no. 1, p. 2100605, 2022.

[193] M. Bont, C. Barry, S. Johnston, and Science, "A review of liquid silicone rubber injection molding: Process variables and process modeling," *Polymer Engineering,* vol. 61, no. 2, pp. 331-347, 2021.

[194] S. R. Hirshorn, L. D. Voss, and L. K. Bromley, "NASA Systems Engineering Handbook," 2017.

Contribution of Individual Authors

Mostafa Sayahkarajy prepared the paper draft. Hartmut Witte supervised the research and revised the paper.

Sources of Funding

This study was partially supported by the Thuringian State Graduate Support.

Conflict of Interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.

Creative Commons Attribution License 4.0 (Attribution 4.0 International, CC BY 4.0)