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Soft robotics: A solid prospect for robotizing the natural organisms

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Abstract. Innovation is considered as key to ensure continuous advancement and firm progress in any field. Robotics, with no exception, has gained triumph and approval based on its strength to address divers range of applications as well as its capacity to adapt new ways and means to enhance its applicability. The core of novelty in robotics technology is the perpetual curiosity of human beings to imitate natural systems. This desire urges to continuously explore and find new feet. In the past, contemporary machines, in different shapes, sizes and capabilities, were developed that can perform variety of tasks. The major advantage of these developments was the ability to exhibit superior control, strength and repeatability than the corresponding systems they were replicating. However, these systems were rigid and composed of hard an underlying structure, which is a constraint in bringing into being the compliance that exists in natural organisms. Inspiration of achieving such compliance and to take the full advantage of the design scheme of biological systems compelled researchers and scientists to develop systems avoiding conventional rigid structures. This ambition, to produce biological duos, needs soft and more flexible materials and structures to realize innovative robotic systems. This new footpath to craft biological mockups facilitates further to exploit new materials, novel design methodologies and new control techniques. This paper presents an appraisal on such innovative comprehensions, conferring to their design specific importance. This demonstration is potentially useful to prompt the novelty of soft robotics.

Keywords: soft robotics; bio-mimicking; bio-inspiration; bio-robots; flexibility; compliance

1. Introduction

Human beings have always been curious in developing systems inspired by the natural systems, to achieve various capabilities of biological structure, like moving, walking and flying. This interest drove humans towards the development of machines. Primarily, only certain drawings and ideas were surfaced showing this strong intent to achieve the talent of a selected or attracted organism. “The Pigeon” of Archytas, as described by Gellius and Beloe (1795), from Greek around 350 B.C propelled by steam, may be considered as one of such primitive efforts (see Fig.

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1). The pigeon, employing a steam boiler, was capable of flying for a few hundred meters merely utilizing the action-reaction forces generated by the steam boiler.

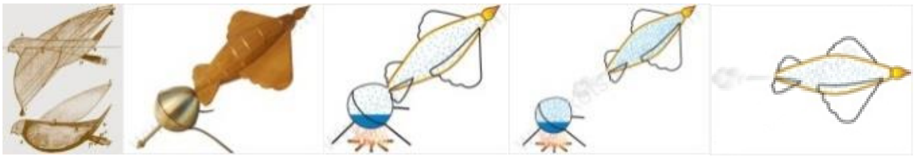


Fig. 1 Pigeons designs: drawing, and steam propelled design idea (Βακουφτσής 2014, Kotsanas 2016)

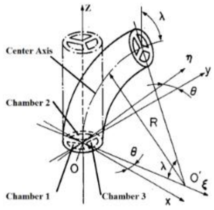
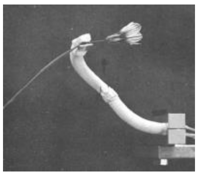


Fig. 2 Three channel FMA structure



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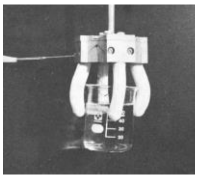

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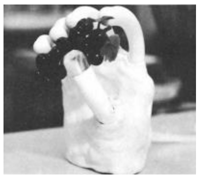

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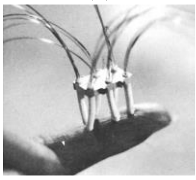

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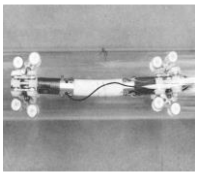

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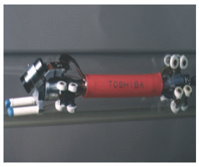
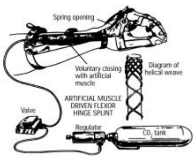


(f)

Fig. 3 Arm, finger, hand, legged, mobile (pipeline inspection) robots based on FMA



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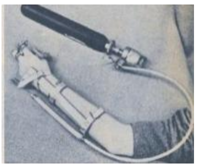


(d)

(e)

(f)

Fig. 4 McKibben muscle design and applications

Leonardo Da Vinci (late 15th Century) can be considered as the modernizer of the field of Robotics. His human and animal inspired robot sketches and models were used by other innovators in the medieval times to build machines.

The Electric Man (1865), the Steam Man (1883), the Automotive Man (1880's), and the Boiler Plate (1893), should be considered as some distinguished imaginations in contemporary past. 1940's can be considered as the sliding partition between imaginations and real time working robots while Isaac Asimov predicted the rise of a powerful robot industry.

Robotics law, by Asimov in 1942 (Clarke 1993), narrated basic guidelines for a complex upcoming man-machine era in simple words, centered at human safety. Soft robotic systems are safer in human interaction as compared to their rigid or hard counterparts, and their control, which is still in the evolutionary process, seems to have higher compliance though may be more complex. For example, soft grippers similar to human finger tips offer stabilized grasping as compared to the rigid grippers and need reduced control system demand (Akella and Cutkosky 1989). Furthermore, soft robots give the impression to be more appropriate for socialization of robotic technology, where a harmless and compliant human-machine interaction is required.

1.1 The maiden companionship

The recent state-of-the-art of bio-inspired soft robotics has been revolutionized from a state which was presented by way of fiction just a few decades ago. Although they are still abstract, now they are being transformed from fictional to factual entities. The development of robotic actuators employing soft materials initiated in late 1980's. Toshiba Corporation's flexible actuator can be considered as the foremost development in the field of soft robotics as shown in Fig. 2.

Toshiba realized a flexible micro-actuator (FMA) for maneuvering micromanipulators and robotic mechanisms in 1989 (Suzumori *et al.* 1991a, b, Suzumori 1989, 1990). Made of fiber-reinforced rubber, the FMA was a three Degrees of Freedom (DoF) actuator capable of producing miniaturized movements pretending fingers, hand, arm and leg actuation. Three dof were designed through three channels which were actuated by electro-pneumatic or electro-hydraulic pressure thus causing axial stretch or bending effect (Suzumori *et al.* 1992, 1993).

Series of connected FMAs can produce increased DoFs for various applications as shown in Fig. 3 (Suzumori 1996, Toshiba.co.jp. 1997). Later on in late 90's, based on nature of application, material and FMA actuation characteristics; different fabrication techniques like molding (Suzumori 1996), extrusion molding (Suzumori *et al.* 1997), and stereo lithography (Suzumori Koga and Haneda 1994) were implemented to craft conforming FMAs (Suzumori *et al.* 1996).

While demonstrating FMA as the foremost soft robotics innovation, it is appropriate to recall, in the context of soft robotics, the invention of artificial muscle for prosthetics introduced as McKibben Muscle in 1957. Although some other fluidic actuators are even older, McKibben Muscle can be considered as the prominent invention in robotics. It was implemented in 1957-58 to actuate hands and fingers of polio affected Karen McKibben, the daughter of Dr. Joseph Laws McKibben (Chou and Hannaford 1996, Hoggett, 2012). The innovative design, by German scientists , incorporated bellows cylinder inflated by carbon dioxide, thus acting as a muscle generated pinching movement of attached paralyzed fingers (Fig. 4).

1.2 The contemporary apprehension

Pneumatic artificial muscles or McKibben muscle also known as rubbertuator may not be considered as the ground breaking for soft robotics, even if relevant, as that invention was purely developed for prosthetics. Furthermore, the muscle was a part of a system which was mechanically rigid at large. Rubbertuators were persistently implemented in the robotics systems for prosthetics and rehabilitation purposes (Pack 1994, Caines 1991, Hamerlain 1995, Groen *et al.* 1996, Alford *et al.* 1997, Wilkes *et al.* 1997, Cambron *et al.* 1998). Therefore, it is perceptible that the ground breaking work for soft robotics was accomplished in late 1980's in the form of FMA development in collaboration of Toshiba Corporation and Yokohama National University Japan. During 1990's, major work was accomplished on the development of soft grippers like human finger tips (Suzumori *et al.* 1994), and on the soft skin development which was utilized both as skin and for touch sensing to improve the human-robot interaction (Yamaha *et al.* 1999, Hakozaki *et al.* 1999). It is also worthy to mention that efforts were made to introduce soft joints making it possible for robotic structures to be more compliant and safer especially while interacting with humans (Bubic 1992). Most of those primary undertakings were originated in Japan, USA and UK.

1.3 Outfit of a soft robot

A soft robotic system generally consists of same elements like a conventional robot including body structure, actuation mechanism, sensors and transducers architecture, electronic and control interface, and power sources (Rus and Tolley 2015). Some of the soft robotic systems may include Human Machine Interface (HMI) as well.

It is necessary to distinguish between soft bodied robots and hard bodied robots with soft-like actuation. Both categories may have impersonation of bio-inspiration and may represent flexible and compliant actuation, however, the objective of soft robots is to embody all elements of a robotic system into soft material avoiding rigid links and mechanisms. This ambition indeed set apart soft bodied robots, composed of soft materials of various grades, as soft-robots (Rus and Tolley 2015, Iida and Laschi 2011). More specifically, both of these categories may have similar morphologies, but they will be differentiated substantially based on materials they are built from.

The soft robots are usually fabricated from elastomeric materials which are organic in nature (Ilievski *et al.* 2011). The advantage of relying on soft materials for body construction of soft robots is the variability of conceivable motions that such materials can offer with a simple structural mechanism (Ilievski *et al.* 2011, Kim *et al.* 2013). Soft actuators which have been employed and are being investigated for soft robots are mainly of four types namely tendons, Pneumatic Artificial Muscles (PAMs), Fluidic Elastomer Actuators (FEAs), and Electroactive Polymers (EAPs) (Rus and Tolley 2015, Ilievski *et al.* 2011). Actuators are generally organized to generate bidirectional motion which offers an added advantage of better compliance. Conventional sensors and electronics are still in use though recently researches have been started to investigate and modernize soft, flexibles, stretchable and bendable sensors.

1.4 Paper organization

This paper provides an insight into general as well as applied soft robotics, and an exclusive appraisal to recent developments in this research area. This paper is organized in five sections including first section on Introduction: Section 2 represents overview of design techniques and materials used for the development of various soft robotic systems. Section 3 presents various actuators and sensors implemented in different soft robots. A selective overview of the bio-inspired state-of the-art is reported in Section 4. Finally, Section 5 comments on the conclusion, key challenges and the future work.

2. Soft robotics design techniques and materials

The core of soft robotics technology is to implant all required components of a robotic system in the body material making it dexterous enough to concert as both brain and body simultaneously (Rus and Tolley 2015). Furthermore, bio-inspiration does not necessarily intend copycat the natural system. The intention is to imitate capabilities of biological systems, conforming to their abilities to generate actions through body deformation ensuing their in-built capacities and Constraints (Trimmer *et al.* 2012) to produce intrinsic mechanical compliance (Fig. 5).

What do we need in a soft robot generally-a flexible body composed of soft material like polymers capable of producing continuum movements; soft actuators like tendons, PAMs or FEAs; sensors and driving electronics which are still conventional mostly; control techniques and power source-the specific components obviously depend upon a specific design and application of a robotic system. Together with material selection, it is indispensable to configure the shape and locomotion of the system. In soft robotics, it is crucial to address material selection, profile design and fabrication, and design of locomotion scheme in parallel to effectively utilize material properties to implement a conforming locomotion gait (Rieffel *et al.* 2014). In this section, various design and modeling techniques are discussed based on their respective robotic models.

As already stated, FMA development and implementation in the late 1980's and 90's was the earliest effort presenting different design methodologies and fabrication techniques for different applications using the same actuator (Suzumori *et al.* 1991a, b, 1992, 1993, 1994, 1996, 1997 Suzumori 1989, 1990, 1996, Toshiba.co.jp. 1997). In 1997, Toshiba Corporation and University of Tokyo, Japan implemented the Finite Element Method (FEM) to analyze characteristics of three different kinds of FMAs-optimized fiberless FMA; non-optimized fibreless FMA; and conventional fiber-reinforced FMA (Suzumori *et al.* 1997). The optimized fiberless FMA was found to be practically more appropriate for low-cost FMA development through extrusion molding process and for the production of disposable micromanipulators for medical applications.

PAMs have also been widely implemented in designing different robotics systems in 1990's (Hamerlain 1995, Stone and Brett 1995, Bowler *et al.* 1996). To realize improved bio-robotic muscle actuation using PAM, in 1999, researchers at University of Washington proposed PAM application with a hydraulic damper to achieve the required force-velocity level along with force-length relationship (Klute *et al.* 1999).

During that early phase, a group of scientists from Stanford University modeled soft fingertips consisted of a soft layer of viscoelastic fluid or powder covered by instrumented skin (Akella and Cutkosky 1989). The design was based on the consideration that human fingertips have better compliance than hard or elastic fingertips and to develop task oriented stiff or soft fingertips. They were able to develop anthropomorphic fingers with 6 DOFs with soft manipulation for various kinematic finger-object couplings like rolling, compression and bending. The fingertip model developed and simulated exhibited a better grasp for sharp corner object owing to energy dissipation technique implemented in the soft fingertip.

Rubber structures follow simple operational principles and mimic natural motion capabilities, however, due to the material and geometric nonlinearities, the design process of pneumatic rubber actuators is tricky. The inherited complexity of these structures needs efficient analysis and simulation techniques to evaluate their deformations. One effective analysis method to solve these non-linear problems is FEM. In 2007, one of the developers of FMA along with other researchers at Okayama University and Osaka University implemented static analysis using non-linear FEM technique to consider correctly nonlinearities in the design and fabrication process of pneumatic

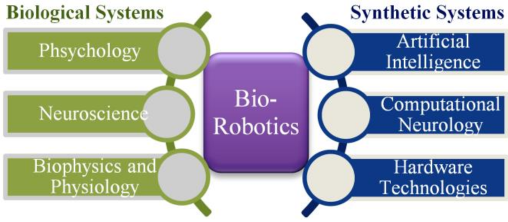


Fig. 5 Bio-robotic correspondence to biological and synthetic systems (Klute *et al.* 1999)

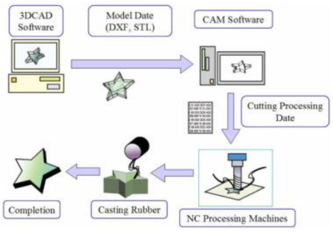
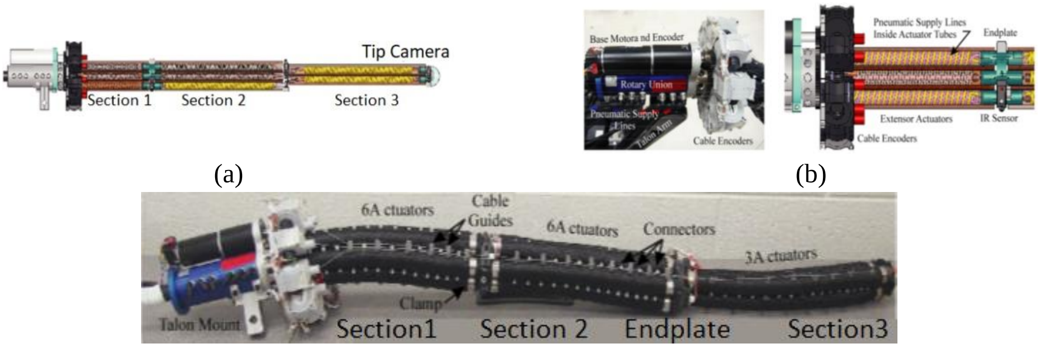


Fig. 6 CAD/CAM system for prototyping actuator



(a) (b)

(c)

Fig. 7 OctArm VI. (a) Arm 3D view, (b) base close-up, close-up of Section 1 and (c) complete arm

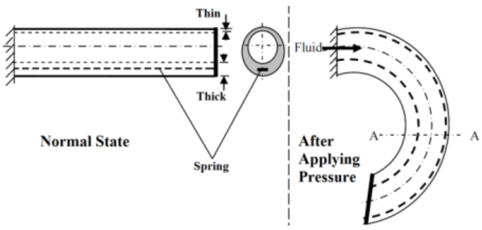


Fig. 8 Single channel FMA gripper

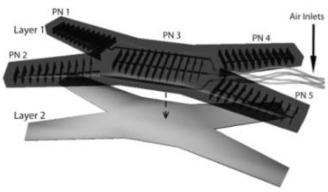
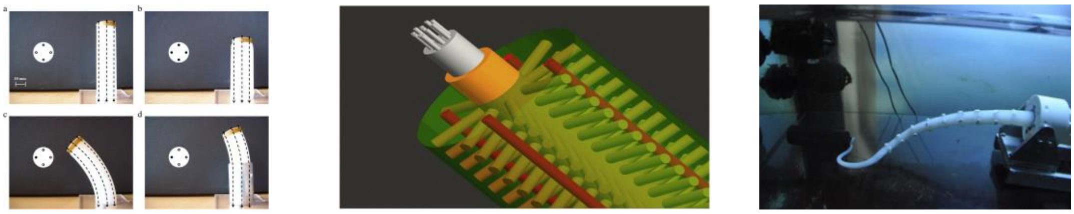


Fig. 9 Schematic of quadruped soft robot



(a) (b) (c)

Fig. 10 (a) Shortening, bending, (b) CAD design, and (c) the prototype of design of octopus arm

(a) (b)

Fig. 11 (a) Schematic of the model and (b) the bending moment profile upon SMA actuation

(a) (b) (c) (d)

Fig. 12 (a) molding, (b) spin-coating the membrane, (c) mounting gripper body and (d) GeckoGripper

rubber actuators (Suzumori *et al.* 2007). This method provided optimal design solution for prototyping by a CAD/CAM based rubber molding process (Fig. 6). A pneumatic rubber actuator with 2 DOF was developed and tested showing off that the characteristics corresponded to the achieved analytical results.

The soft robotic manipulators are being aimed to offer dexterousness maximizing the load capacity for available power or force to the manipulator. In 2000's, a consortium of various Universities and research agencies in USA, developed a series of octopus/elephant-trunk inspired pneumatic manipulator, OctArm I-VI (Pritts and Rahn 2004, McMahan *et al.* 2006, Grissom *et al.* 2006, Trivedi *et al.* 2008a, b, Trivedi and Rahn 2014). Initially developed in 2004 (Pritts and Rahn 2004) scientists at The Pennsylvania State University, USA further described an optimal design methodology for OctArm-VI prototype in (Trivedi *et al.* 2008a). The design of this manipulator incorporated the ability of the arm to manipulate objects. On the basis of its ability, a dexterity template was suggested defining wrap angles for different sections of the arm. The tube thickness and length of each section were calculated for base diameter and total arm length for desired configuration of the manipulator. It was realized that the optimal design depends on the ratio of maximum pressure applied to the manipulator to the Young's modulus of the manipulator's material. That result led to the conclusion that an optimal design would be valid for a family of manipulators with constant pressure to the young's modulus ratio. Certain limitations were also found including unstable optimal performance as load capacity maximized only for certain test pressures; and some design conditions were not addressed like elastic stability, out-of-plane deformations, and torsion.

These researchers further investigated and proposed geometrically exact models for soft robotic manipulators (Trivedi *et al*. 2008b) highlighting certain inaccuracies in the previous models of OctArm.

The alternate model, OctArm V incorporated material nonlinearities, gravitational loading and payload variations, and demonstrated reduced error to 5% which was 10 times more accurate than the previously investigated models. Various shape estimation methods were further demonstrated in (Trivedi and Rahn 2014) employing the latest model of OctArm VI (Fig. 7). The detailed design is discussed in section IV.

Single channel technique was implemented to develop an FMA based soft gripper (Fig. 8) accommodating asymmetric wall thickness of the tube in 2010 (Udupa *et al.* 2010). Symmetric neoprene tubes were cut and joined together to form asymmetric actuator. The strength of the tube was reinforced using a flat spring on the thicker side of the tube.

A novel quadruped soft robot was designed and fabricated implementing soft lithography technique in 2011. The mold was created by three-dimensional (3D) printing to fabricate the robot body. Pneu-net (PN) architecture (Shepherd *et al.* 2011) was employed to design pneumatic channels as it is highly compatible with soft lithography technique (Fig. 9).

Considering the high dexterity, variable stiffness and complex behavior of octopus arm, Scuola Superiore Sant'Anna, Italy presented a novel design concept to imitate it in 2011 (Cianchetti *et al.* 2011). The design incorporated some of the important features of octopus arm like elongation ability, bending capability in all directions, and stiffness control. The design represented an arrangement of longitudinal and transverse silicone based muscles forming an artificial muscular hydrostat (Fig. 10). Different molding techniques implemented to fabricate and test different kinds of muscles for this design. The design and experimentation exhibited that the muscle placement is the key along with the actuation capabilities to achieve octopus like performance.

With the same inspiration, another group of the same institution deliberated another approach to mimic octopus arm in 2012. A cable driven conical shaped manipulator, made of silicone, was designed that was tested in water to take the advantage of the mechanical properties of the material (Giorelli *et al.* 2012). To control and assess the design characteristics, direct kinetics model was evaluated by geometrically exact approach and jacobian was implemented for inverse kinetics model. The developed models were tested and found suitable with a good degree of accuracy for the fabricated manipulator. Some cable configuration based inaccuracies were also highlighted including friction, out of plan cable adjustment, and tip error.

A three-finger soft gripper with two DOF at each finger, mimicking human gripping, was realized by embedding three shape memory alloy (SMA) springs in silicone elastomeric tubes at University of Science and Technology, China in 2013 (Obaji and Zhang 2013).

The design was developed to investigate the force distribution mechanism of the SMA actuators in the soft tubes and to testify that such actuators can substitute conventional solid state actuators. Two springs, placed on one side of the tube, bends into U-shape with applied current and the third spring acts as an auxiliary mechanism establishing a stable grip profile (Fig. 11).

An adhesion based gripper employing microfibers, GeckoGripper, was designed at Carnegie Mellon University, USA in 2014. A 3D printed syringe pump was used to apply air pressure on a soft inflatable membrane to change the stretch configuration for gripping and un-gripping. The microfiber and the membrane were molded and spin coated respectively using polyurethane elastomers. The 3D printed body was attached to the membrane during the curing time (Fig. 12).

The above section has described a certain set of various designs and techniques reported in literature that were developed based on inspiration from different biological systems or species. The set of research reported in literature indicates an extensive shift towards flexible and soft continuum robotics. However, many systems are implementing similar design techniques exhibit similar kind of constraints and complexity in the control and manipulation. These techniques and methodologies should be further explored and experimented to realize smarter mechanisms. Furthermore, along with improvement in design methodologies, the control architecture approaches may require emphasis in order to accelerate the research in this novel area of robotics technology. The core of the soft robotic design is the embodied intelligence, manipulation and control, which is on its way with the extensive and dedicated efforts being made.

3. Review of sensors and actuators in soft robotics

There are different kinds of commercially available sensors, being implemented in soft robotics, which are originally developed and used for conventional robotics. Actuators for soft robotics have a better recitation as more efforts can be witnessed towards actuators development in soft robotics. The nature and spirit of soft robotic mechanisms demand realization and development of soft and flexible sensors and actuators to make more dexterous and exclusively soft and compliant robotic systems. This section compliments the efforts, which have been made towards the development and experimentation of soft sensors and actuators, as reported in literature. Sensors are still in early development consideration in soft robotics, and therefore, actuators got more prominence.

We have already described FMA and PAM actuators. The FMA has been implemented widely for different kind of soft robotic systems (Suzumori *et al.* 1991a, b, 1992, 1993, 1994, 1996, 1997, Suzumori 1989, 1990, 1996, Toshiba.co.jp. 1997). It is a rubber actuator (Fig. 13) incorporating stretching actuation mechanism and offers multiple DOFs like pitch and yaw along with stretch; however, these are inter-dependent DOFs. It has many advantageous characteristics especially its capacity to act as the actuator as well as the body of the robot. Due to this property, miniaturized systems can easily be designed and constructed. Its actuation is smooth owing to its frictionless mechanism. FMA based systems can be developed using different fabrication/molding techniques for various system designs and applications (Fig. 3).

The McKibben actuator or PAM is also very effective making a robotic system light, cheap, compliant and offers easy maintenance. It has wide range of application in anthropomorphic designs, and assistive robotic mechanisms (Fig. 14).

A plastic bellow tube actuator was presented at Bristol University for a gripper design in 1995. It can be considered a fine effort towards evolution of soft robotics as the idea was novel; however, the actuator was not completely soft. The airtight bellowed tube was attached to a steel strip, which upon air pressurization exhibits curling movement which could be utilized for grasping and gripping (Stone and Brett 1995). A customized tactile sensor was also designed for the gripper for strain measurement by arranging strain gages on the steel strip (Fig. 15).

A rotary-type soft actuator, ASSIST, was developed at Okayama University Japan in 2004-2005 (Sasaki *et al.* 2005). The actuator was composed of rubber tubes and fiber reinforced polyester bellows. The mechanism was controlled by pressure control system. The actuator was implemented in two different configurations; one employing McKibben muscles and the other

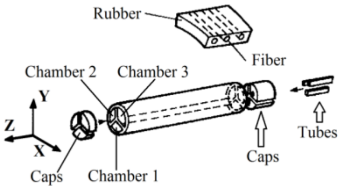


Fig. 13 The FMA structure

Fig. 14 Pneumatic muscle actuator (Bowler *et al.* 1996, Anon 2010)

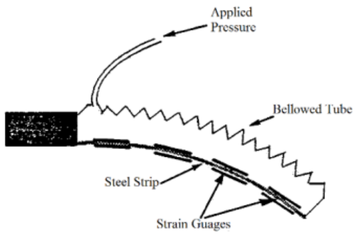


Fig. 15 Pneumatic actuator construction

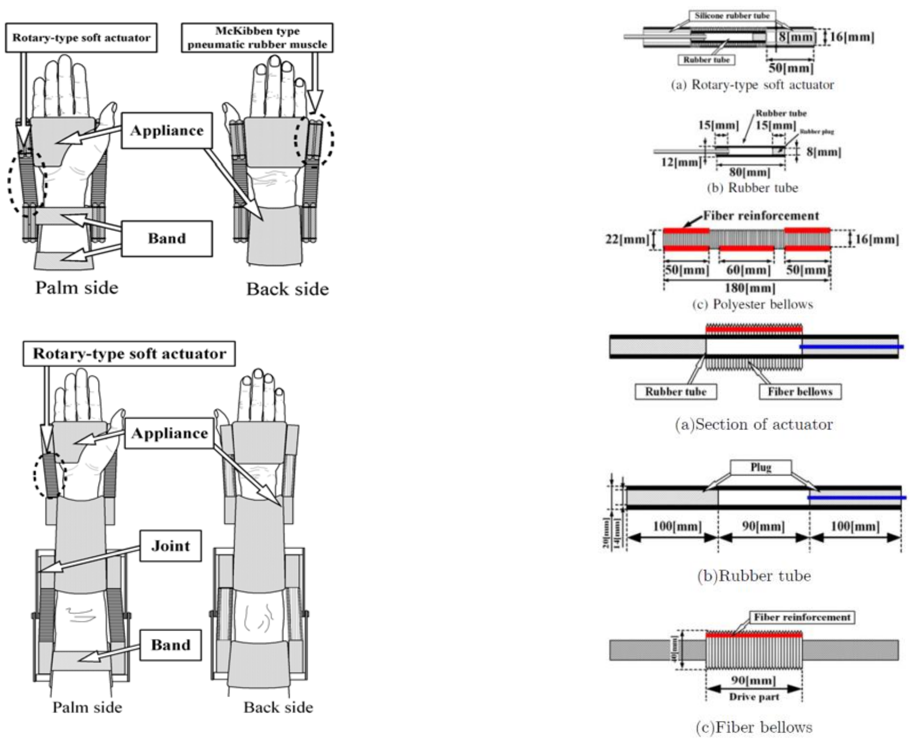


Fig. 16 ASSIST actuator designs

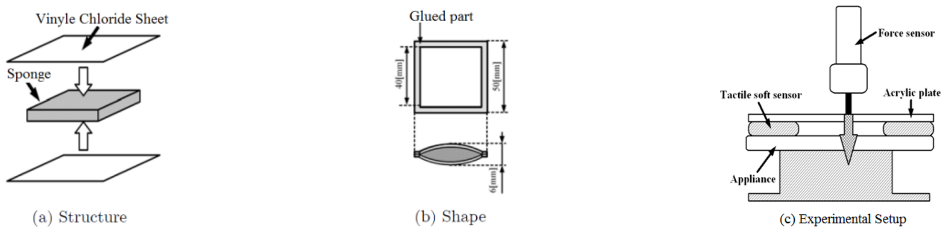


Fig. 17 Tactile sensor

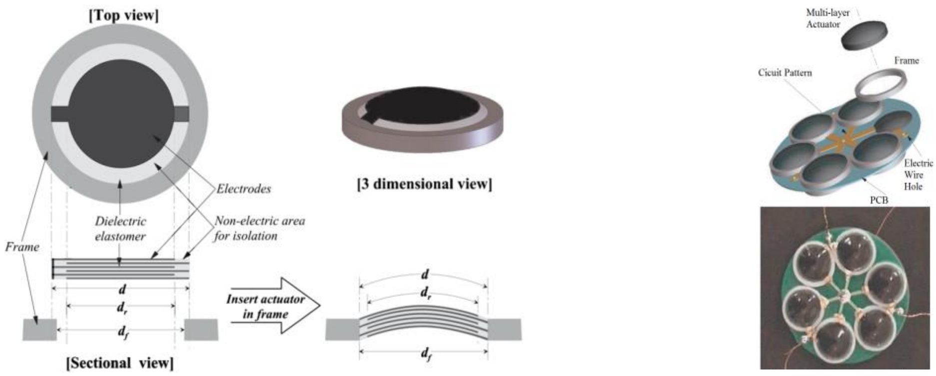


Fig. 18 Construction and prototype of DEA actuator

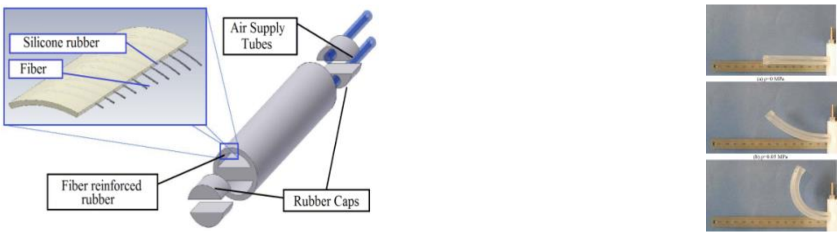
without that. This actuator was designed for assistive motion of wrist. The McKibben muscles were used in the initial design and were attached to the palm mechanism for releasing the appliance control while it was nonoperational. The alternate design (Sasaki *et al.* 2005) was further implemented for wrist and elbow motion assistance (Fig. 16).

Tactile soft sensor was implemented to calculate and detect the movement of the forearm (Fig. 17). Bending angle of wrist and elbow, and human muscle power measured by electromyography (EMG) were incorporated to evaluate and determine the effectiveness of the actuator. An ASSIST equipped person can move the arm and hand with lesser muscular power as compared to an unequipped one.

OctArm design has already been described in section II. Its pneumatic actuator was designed considering five parameters: length based on target wrap angle; outer radius based on available mesh size and required mesh angle; structural stiffness and to meet required load capacity, appropriate tube thickness was selected; tube material was identified for desired extensibility and pneumatic permeability; and finally mesh angle was critically and experimentally selected to achieve the desired actuator performance (Pritts and Rahn 2004, McMahan *et al.* 2006, Grissom *et al.* 2006, Trivedi *et al.* 2008a, b, Trivedi and Rahn 2014).

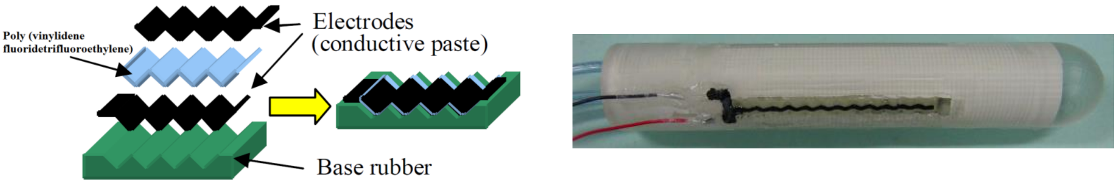
Another novel actuator, to drive an annelid robot, was developed at Sungkyunkwan University, Korea utilizing dielectric elastomer actuator (DEA) which has the maximum deformation amongst the available electroactive polymers (EAP) (Jung *et al.* 2007). A thin layered sheet of the elastomer is connected to a rigid frame (Fig. 18). The elastomer expands in convex or concave profile with compressive force. This expansion generates actuation avoiding time-dependent and pre-strain actuation. These actuators were connected serially to develop the earthworm robot.

Another pneumatic rubber actuator, already mentioned in section II, was developed



(a) (b)

Fig. 19 (a) Actuator and (b) experimentation results



(a) (b)

Fig. 20 (a) Construction of piezoelectric polymer sensor and (b) its attachment on FMA

incorporating geometric, material and contact non-linearity characteristics for desired actuation by using non-linear FEM (Suzumori *et al.* 2007). Nylon reinforced rubber was used to design a 2 DOF actuator with 2 independent tubes. Simple pressurized bending and stretching actuation has been generated. Where the actuation technique is simple, the design of such actuators is quite complex which is based on shape of tube cross-section, length and rubber elastic properties. The actuator (Fig. 19) was employed to design a Manta swimming robot.

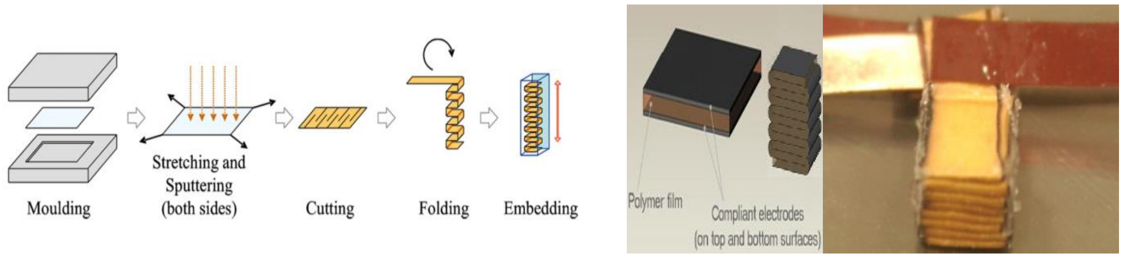
Keeping in view the compliance required between soft actuators and sensors, and to avoid high stiffness in conventional potentiometers and optical encoders, scientists, including the developer of the FMA, at Okayama University, Japan developed a soft displacement sensor composed of piezoelectric polymer as deformation sensing element, conductive paste as electrodes, and base rubber (Fig. 20). The soft sensor was used to produce and intelligent FMA actuator, which was capable of implementation in the development of flexible hand due to its improved grasping mechanism (Yamamoto *et al.* 2007). Experimental results varied positioning accuracy; however, hysteresis and noise were detected as well. The technique used for the fabrication of the sensor and experimentation results exhibited that tactile or force sensors can also be developed for flexible mechanisms for higher accuracy and control.

The above sensor has a wave type pattern. These scientists developed and tested both straight pattern and waved sensors and found that straight sensor has stronger signal strength but with high signal to noise ratio. The wave patterned sensor output has high linearity, however, the signal strength is low (Kure *et al.* 2008).

Considering the need of softness and back-drivability required to realize bio-mimicking soft robots, scientists at SSSA proposed an electrostrictive actuator composed of platinum silicone rubber compound EcoflexTM 01-10 and 00-30 (Smooth-on, USA) as dielectric material.

The material selection was made on the basis of properties and compliance found during tensile-compression tests that were carried out on various elastomeric materials (Cianchetti *et al.* 2009).

A thin film of the silicone, covered with thin gold film as compliant electrodes on both sides,



(a) (b)

Fig. 21 (a) Electrostrictive actuator fabrication and (b) and the prototype

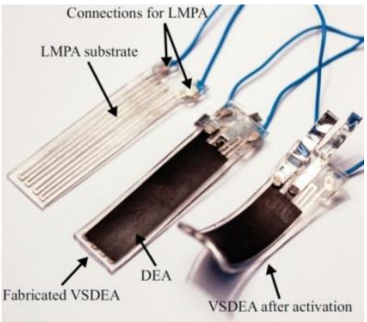
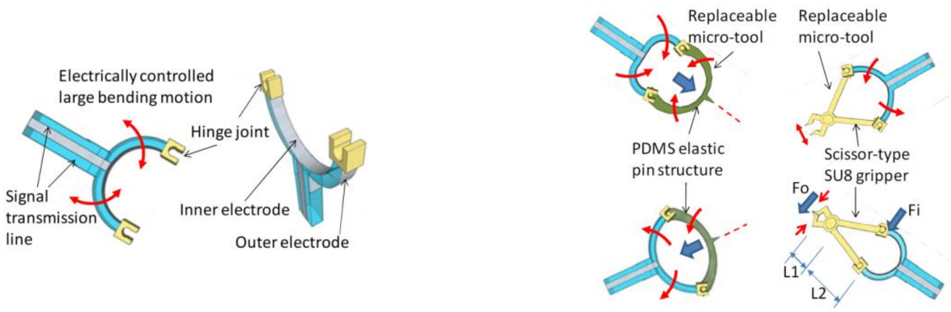


Fig. 22 VSDEA actuator construction



(a) (b)

Fig. 23 (a) IPMC actuator construction and (b) applications

was folded in a number of turns using a customized device to achieve well aligned layers and folds. Electrode connections were facilitated through little strips of Kapton sheet with silver conducted glue CircuitWorks 7100. The whole package was finally wrapped in a thin layer of silicone to form the actuator (Fig. 21). The actuator was employed to develop an Octopus arm model (Laschi *et al.* 2009). These scientists have developed octopus arm employing SMA based spring actuator as well (Follador *et al.* 2012, Cianchetti *et al.* 2014).

A flexible pneumatic robotic actuator (FPA) was proposed by Chinese scientists in 2013 composed of elastic silicone rubber with embedded spring for stiffness and radial deformation prevention. It was used to design different joints and grippers to manipulate different things and a climbing robot mechanism keeping in view the compliance, adaptability and safety that conventional rigid robots lack (Bao *et al.* 2013). Although this actuator has been applied for rigid mechanisms, it is appropriate to report here keeping in view its potential of application towards soft mechanisms development based on properties it has exhibited.

A novel variable stiffness dielectric elastomer actuator (VSDEA) was developed by École Polytechnique Fédérale De Lausanne (EPFL), Switzerland in 2015. The actuator was composed of pre-stretched DEA attached on low-melting point-alloy (LMPA) substrate (Fig. 22), capable of bending due to change in LMPA stiffness upon heating (Shintake *et al.* 2015). The actuator was employed as fingers for a gripper prototype. The self-sensing ability of the actuator, its stiffness changing capacity, and potential dynamic behaviors make it a potential actuator for flying, swimming, and surgical robotic applications.

To manipulate micro-soft objects like cells, scientists at University of Chung Cheng, Taiwan, realized an ioconic polymer metal composite actuator (IPMC) with arched bending actuation (Feng and Yen 2015). The actuator was employed for scissor mechanism for gripping force enhancement. An elastic pin, attached to the actuator joints, converted arched motion of the actuator into linear motion (Fig. 23). The actuator was fabricated using Nafion through a micro-mold which was developed using a die developed by photolithography. The model was selectively inactivated through photoresist to deploy platinum electrodes which were deployed through a chemical process. Ion exchange method applied to remove photoresist effect. The actuator was capable of producing 10nM force and 100 µM displacement.

Bio-inspiration has driven researchers to comprehend actuators for desired locomotion and mechanisms development. Tendon driven, SMA based, pneumatic and fluidic actuators have been realized and employed for various bio-mimic systems. In contrast to actuators, flexible sensors development and realization has to go long way, as the conventional sensors are still in wide practice in soft robotics. For soft robotics, it seems ultimate to exploit new materials and techniques to move further towards the development of flexible and compliant sensors and more efficient actuators.

The next section is an exclusive appraisal on the state-of-the-art of bio-inspired systems that have been designed and developed alongside the realization of required techniques and resources.

4. State-of-the-Art

It is evident from previous sections that the implementation of various novel techniques, exploration of appropriate materials, and efforts that are being made towards designing of soft sensors and actuators describe the functional importance of bio-inspired soft robotic systems. This fascination has steered some high-tech developments in this field. From McKibben based systems to FMA structures, and tendon driven to SMA based designs, substantial contributions have been made to imitate natural living beings. This section presents an insight on some state-of-the-art bio-inspired systems which have been evolved owing to the novel aspiration of soft robotics.

4.1 FMA based compliant mechanisms

Some of the earliest soft robotic mechanisms which were developed by utilizing different configurations of FMAs with 3 DOFs exhibiting pitch, yaw and stretch have already been presented in Fig. 3 in section-I.

A 7 DOF arm with snake-like motion configuration (Fig. 3(a)) was developed by serially connecting two FMAs and attaching a fiber reinforced rubber gripper to the manipulator. The arm experimentation indicated two important effects: compliance can be controlled by regulating the feedback gain; and that the compliance control enhances the stiffness of soft mechanisms for desired manipulation (Suzumori 1996). Fig. 3(b) shows an FMA gripper having a load capacity of 500 gram-force (gf) with two dimensional compliance controls: one in gripping direction and the other lateral. The four finger gripper revealed lateral movement around the gripper's center axis, when the fluid pressure reached certain maximum limit, which might be effective for nut fastening and bottle cap opening-closing operation. Experimentally, this gripper achieved 0.01 Nm torque and 0.25rps maximum speed (Suzumori *et al*. 1991a). A human-like hand model (Fig. 3(c)) was developed for experimentation purposes to handle delicate and soft objects and to observe different daily life applications of hand. A walking robot, of 1 g weight and 15 mm length with 20 cm/min speed and 300 mgf payload capacity, was design using 6 FMAs (Fig. 3(d)). It utilized 18 pneumatic channels for multi-directional movement with independent control of each leg. 12 pneumatic tubes were considered enough for Omni-directional manipulation. Fig. 3(e) is an inspection robot for 2 inch pipeline. The robot is maneuvered with wheels inside the pipeline while FMA structure facilitated adaptability for varying diameter due to encrustation inside the pipe; and compliance along the curves, bends and elbows owing to its passivity. An amended version for 1-inch pipeline, with a pneumatic micro gripper and a CCD camera was later developed in 1999. That upgraded robot as shown in Fig. 3(f) (Toshiba.co.jp. 1997) was capable of climbing inside pipes, retrieve object from pipeline and was able to pull 5 meter cables including electric and pneumatic channels (Suzumori *et al.* 1999).

These earliest developments have described the relationship amongst the material properties and the respective conceivable compliance. These initial efforts appraised that it is pertinent to use soft materials for the structural development of the robotic systems to achieve higher compliance.

4.2 Inch-worm pipe inspection robot

In early 2000's, an elastomeric two head flexible robot with two bladders was developed at University of Cagliari, Italy (Bertetto and MRuggiu 2001). Two heads on both ends of the tube body of the robot were holding sensors and payload, and transmitting driving air pressure through pneumatic channel. The bladders were facilitating robot manipulation inside the pipes and produced gait through its designed actuation sequence with the tube: the tube stretched and shrunk upon pressurizing and depressurizing while the bladders radially engage and disengage with the pipe surface (Fig. 24) imitating the inch-worm motion.

The robot performance was experimentally validated employing a pipe of 100 mm inner diameter. The optimal gait achieved was approximately 140 mm, that was 40% of the robot resting length, with a 0.6 bar driven pressure and 41 seconds gait time. The experimental model verified the numeric model. The robot model was capable of predicting robotic behavior for varying pneumatic pressure, and pipe characteristics like material and network path. This robot provided an insight into the soft robot gait and position control.

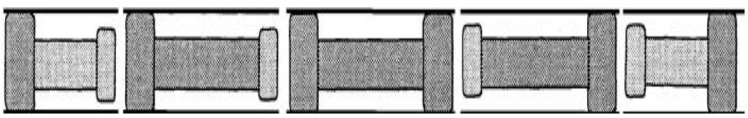


Fig. 24 Gait Pattern of inch-worm pipe inspection robot, from left to right

Fig. 25 ASSIST wearable device for weak muscular power for forearm and hand

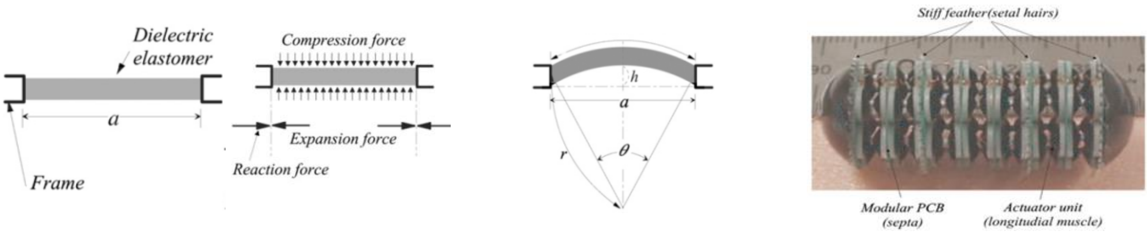


Fig. 26 Annelid earthworm robot, (a), (b) and (c) actuation principle and (d) body of the robot

4.3 ASSIST- pneumatic wearable assisting device

Robotics has long been serving the need of human assistance both in industrial and social sectors. Prosthetics, rehabilitation and care for elderly people are amongst the major assisting capacities of this technology. Soft robotics has the strength to serve these areas owing to its flexibility and compliance. Considering these views, ASSIST was developed for forearm and hand movement, for elderly people making them independent of human assistance (Sasaki *et al*. 2005).

The device (Fig. 25) was designed keeping in view the average arm angular motion capacity of a Japanese male. With high power-weight ratio and mechanical compliance, it is composed of plastic frame which acts as an interface between its actuator and the human arm. Upon pressurization, the actuators move circumferentially with a payload of 4 kilogram in addition the normal weight of arm and hand. Tactile sensor is employed to measure the change in center of pressure, between the arm and the device, when the arm bends. This approach is to identify the human intention which is then further used to control the device motion. The devised control method for ASSIST was recommended to be improved for better maneuverability. It was experimentally verified based on EMG signal measurement, that elderly or people with decreased muscular power can be beneficiaries of ASSIST.

4.4 Compliant annelid robot

One of the major orientations of soft robotics is to develop soft bodied robots capable of unstructured motion. Annelid has inspired such maneuverability. An earthworm robot was developed at Sungkyunkwan University, Korea in 2007 (Jung *et al*. 2007). The DEA actuators (Fig. 18) were serially connected to develop this micro robot with 1 mm/s speed at 5Hz. 8 modules of actuators, consisting of 12 actuators each, were acting both as the body and the actuation units for the robot. Actuators were electrically powered and were connected together using micro silicone cylinders. A silicone based artificial skin with 100 µm thickness was used to cover robot in order to protect the internal components. Mechanical actuation, caused by compressive force of the elastomer actuator when excited, was used as operational principal of the robot (Fig. 26).

4.5 Manta swimming robot

Rubber actuators, the embodiment of most of the soft robots, are quite suitable and better actuation performance in water as a result of water resistance, smooth deformation compliance with water, high power density and light weight. This compatibility urged scientists to design and implement a rubber actuator (Fig. 19) to develop Manta swimming robot with a speed of 100 mm/s (Suzumori *et al.* 2007). Two actuators, each connected with two soft pneumatic channels controlled through electro-pneumatic servo valves, were embedded in rubber structure of the robot (Fig. 27). Both the actuator and the robot were designed using non-linear FEM in order to realize an optimal design considering the geometrical and material non-linearity.

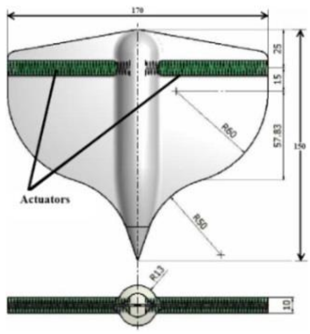


Fig. 27 Manta swimming robot

(a) (b)

Fig. 28 Tetrapod robot, (a) undulation and (b) crawling

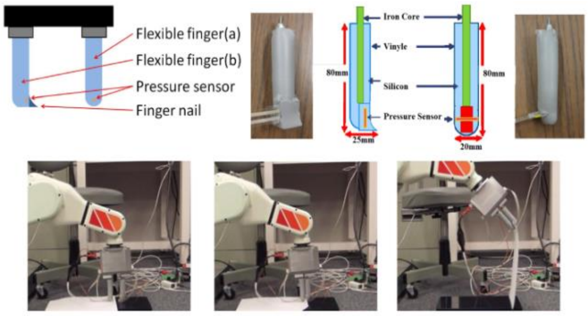


Fig. 29 Soft fingered gripper design and pickup sequence for paper

4.6 Tetrapod multigait soft robot

Inspired by the animals with hard exoskeleton like worms and starfish, Harvard University developed a pneumatic quadrupedal soft robot employing especially designed 5 actuators (Fig. 9). The robot was developed with simple design to produce mobility without emulating any specific locomotion in living organisms. Ecoflex and poly (dimethyl siloxane) was used to develop actuating and strain-layers respectively, of PN pneumatic channels for the actuator (Shepherd *et al.* 2011). Four actuators were designed as 4 legs of the robot while fifth actuator was serving as the spine and used to connect 4 legs of the robot. PN channels produced curling motion of actuators upon pressurization, which in a sequence generated undulation and crawling (Fig. 28). This is a typical demonstration of complex mobility using simple actuation mechanism. However, the experimentation also showed non-linear actuation behavior, which suggests the development of predictive modeling techniques to effectively develop nonlinear motion control system for soft robots.

4.7 Two-fingered parallel soft gripper

Human fingers dexterity has always been an inspiration and challenging for scientists to imitate. Academic research has realized various soft grippers including mimics of human hand and fingers (Bogue 2016). In 2012, researchers at Shibaura Institute of Technology, Japan realized a two-fingered soft manipulator for picking up thin materials like paper and plastic cards through sliding and raising motion sequences (Takashi *et al.* 2012). Fingers are composed of silicone with vinyl covering and central iron core to connect with the hand. One finger is equipped with a soft nail for sliding under the object and then raising it for gripping with the second finger replicating human finger motion pattern. Pressure sensors were embedded inside the fingertips to measure the required pressure for carrying out the sequencing motions (Fig. 29).

6-axes articulated robotic arm was used to manipulate the designed gripper. The gripper has optimal gripping force from 1-3 N and it has found to be appropriate for softer materials like paper for which its success rate of gripping was greater than 90%. For hard materials like plastic cards, this gripper was not found suitable and flexibility and compliance in the fingers is required for such materials.

4.8 Octopus arm inspired soft robotic designs

Service tasks in daily life are quite unstructured and need robotic manipulators with a dexterous compliance and flexibility. The most inspirational living mechanism for soft roboticists that has multidirectional and multipoint bending, soft and deformable body that can stiffen itself, and has good strength of gripping as well, is the octopus arm (Cianchetti 2013). Different soft mechanisms have been developed based on octopus arm morphology, using different techniques in recent years.

SSSA, Italy developed an artificial muscular hydrostat (Fig. 10) capable of producing motion patterns similar to the octopus arm (Cianchetti *et al.* 2011). Three different silicone based mock-ups of the octopus arm were molded using different techniques in order to test the elongation, shortening, bending and stiffness keeping in view the muscular hydrostat of octopus longitudinal and transverse muscles. These designs and prototype modules verified that muscular arrangement is the key in order to realize embodied intelligence, which is required for imitating complex motion patterns of reaching, grasping, and pulling, of the octopus arm. In another effort, the institute developed a redundant mechanism employing 6 limbs capable of pushing itself in forward direction (Calisti *et al.* 2012). Each limb was made of silicone attached to a plastic base with two DC motors. Pushing thrust was provided through a motor driven steel cable. For grasping an object, the pulling force and bending was provided through actuating nylon fibers in a particularly designed limb for the purpose. Locomotion gait was based on pushing and pulling while redundant limbs stabilizing the robot.

This research institute further evaluated mechanical skills of the octopus arm, developing task specific instruments and measurement conventions, in order to suggest suitable materials and actuation strategies to develop replicated robotic systems (Margheri *et al.* 2012). The properties of the octopus muscular hydrostat related to its stiffness, structural support and movements were examined to understand its ability to act as skeleton and effector simultaneously. Based on the identified morphological strength, qualitative description and quantitative studies of musculature, and functional abilities of an octopus arm, a dexterous robotic system was developed replicating its compliance, elongation and force capabilities (Mazzolai *et al.* 2012).

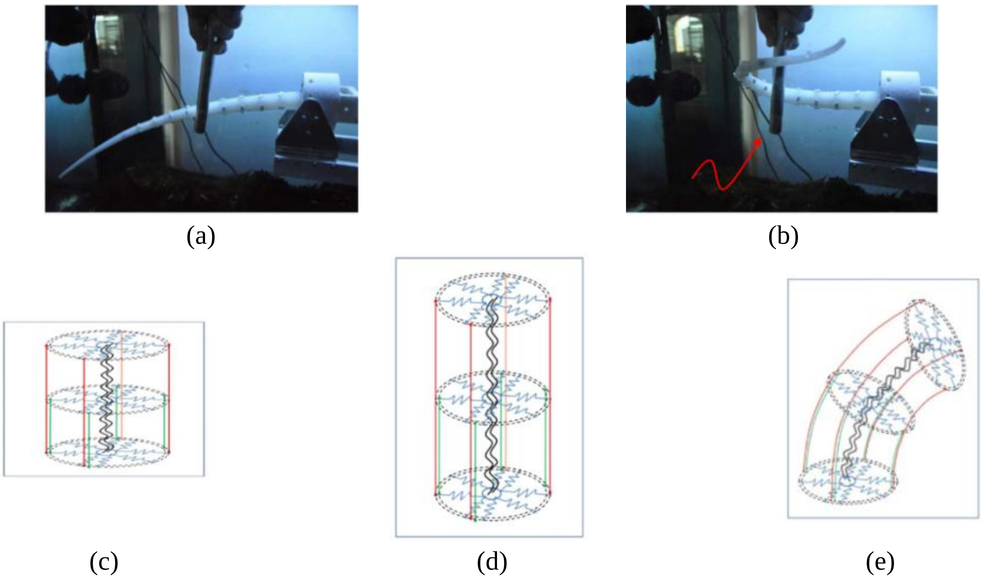


Fig. 30 (a) and (b) show Octopus arm prototype in operation, (c) illustration of the transverse and longitudinal actuators architecture, (d) demonstrating stretching movement and (e) bending motion

Fig. 31 Tendon driven octopus arm prototype

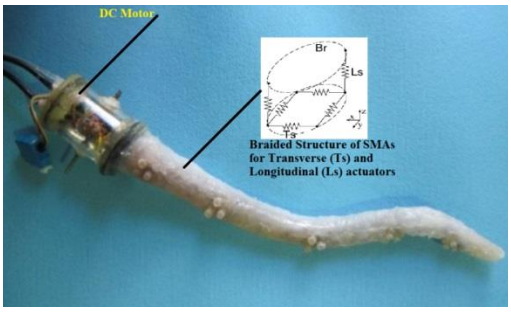


Fig. 32 Tendon driven octopus arm prototype

Silicone (ECOFLEXTM series 00-30, Smooth-On, Inc., with 1070 kg m^{-3} density) was used to develop a robotic system with SMA helix for transverse actuators, and longitudinal cables (covered with sheaths to reduce friction and avoid silicone damage) for longitudinal actuators. 70° transmission angle through crosslinked fibers with longitudinal axis for shape change, 3.3N force for 20% diameter contraction and 70% elongation were achieved. Additional elongation can be achieved using sinusoidal arrangement of electric cables. The module can be considered as a dexterous translation into robotics employing underlying actuation principals of a biological system (Fig. 30).

In another work by the same institute, a tendon driven geometrically exact steady state model of the octopus arm was developed (Renda *et al.* 2012). 2D direct and inverse kinetic models for the control of conical shaped arm were examined to achieve good degree of accuracy (Giorelli *et al.* 2012) demonstrating strength of algorithm to extend for 3D manipulation. A single piece silicone conical shaped module was used to develop that continuum manipulator (Fig. 31). Plastic discs were mounted at various points in the silicone arm tube, during the fabrication, which served as encourage for tendons to drive the arm. The arm can be manipulated in 3D, by pulling the tendons from the base, and the motion patterns depend upon the tendons encourage position. The steady-state model was developed considering the tendons' strain only, to make it simple. Analytical model with one tendon and FEM models were validated against the real prototype. Bending and fetching movements were evaluated through single tendon and three tendon-encourages respectively. The model has generalized structure which can be used to design and test various kinds of slender continuum manipulators.

A modified design of the tendon driven octopus arm that employed SMAs for transverse and

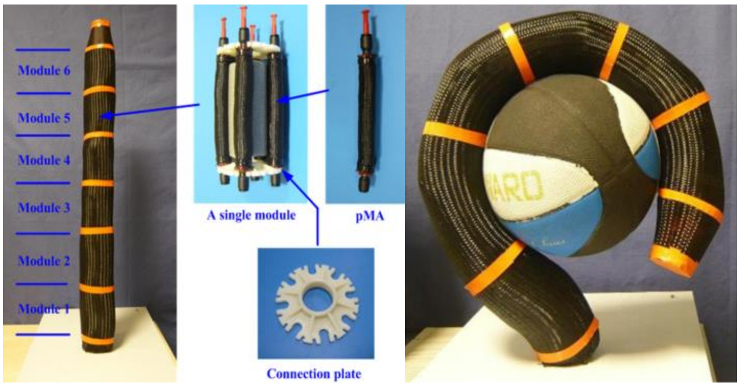


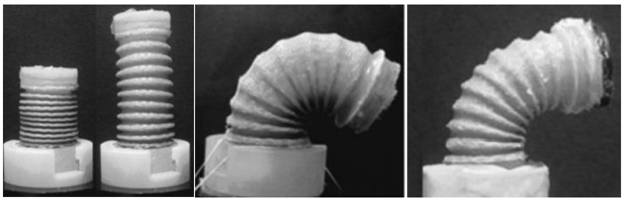
Fig. 33 PAM based octopus arm module

longitudinal actuation is shown in Fig. 32 (Cianchetti *et al.* 2014). The tendon was actuated utilizing a DC motor at the base of the arm to provide grasping mechanism. Helical shaped SMA wires with 0.2 mm diameter were used to form the spring with 1.4 external diameter incorporating 10-20 coils for transverse and 30 for longitudinal actuators. The SMA was actuated through supplied pulse width modulated (PWM) current signal and the cooling of the SMA was passive which was facilitated by filled mineral oil contained in the silicone skin of the arm. The module exhibited successful grasping and manipulation of different shapes, sizes and weights demonstrating fine octopus like movements and capabilities.

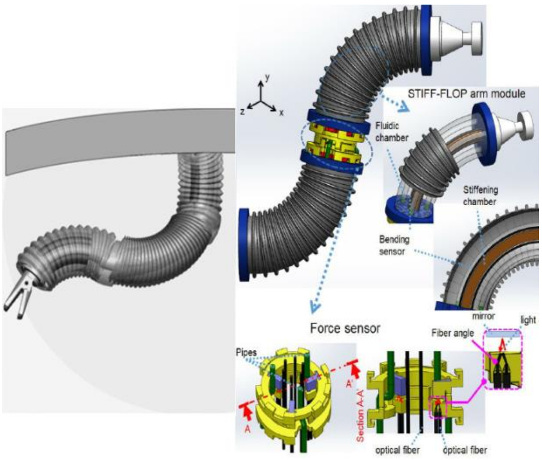
Hyper redundant DOFs and continuum biomechanics of the octopus has further inspired a diverse group of scientists from Italy, China, UK and USA to develop a PAM based module with adaptive behavior or embodied intelligence (Kang *et al.* 2013, 2016). An actuating module was constructed employing 4 PAMs while the robotic arm module is assembled by serially connecting 6 actuating modules (Fig. 32). In this module, PAMs act as both transversal and longitudinal muscles owing to their dual degree of stiffness (DOS), and tensile and compressive strength. Neural network based control of the arm was also developed, considering the octopus nervous system, making it less computational and more reliable. This module (Fig. 33) is potentially applicable for minimally invasive surgery and rescue applications.

Octopus morphological inspiration and operational capabilities have endowed an innovative paradigm to the field of soft robotics. The above discussed designs and approaches are fresh and maiden efforts towards the manifestation of dexterous soft mechanisms.

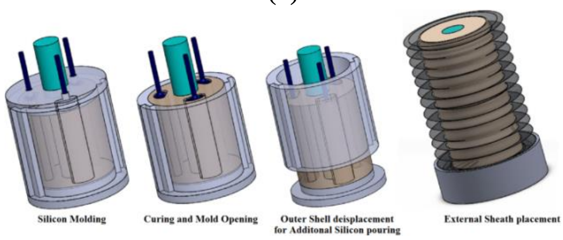
Another octopus arm inspired model for minimally invasive surgical applications was proposed employing granular jamming phenomenon in combination with especially designed fluidic actuation mechanism (Cianchetti *et al.* 2014, Noh *et al.* 2014, Ranzani *et al.* 2016). A modular structure (Fig. 34(a)) was proposed making each module capable of identical functioning manipulation and operational stiffness. The arm (Fig. 34(b)) is capable of safe squeezing, omnidirectional multi-bending and modulated arm stiffness. Three fluidic or pneumatic actuators were radially placed inside an elastomeric cylinder (Fig. 34(c)). The excitation of a single or a combination of fluidic actuators produced required bending. Radial expansion of the elastomeric cylinder was avoided by covering it in undulating sheath. The module is capable of reducing its diameter based on its squeezing strength and thus can be fit into various access requirements. The stiffening chamber, which was placed at the center of the cylinder and the fluidic actuators, was filled with coffee powder and stiffness tuning was achieved through vacuum level control. The



(a)



(b)



(c)

Fig. 34 PAM based octopus arm module

proposed module achieved 40% squeezing and 46% stiffness with an elongation of 86.3% at 0.65bar applied pressure. Bending angle of 120° or 80° was attained with one or two channel actuation respectively. The STIFF-FLOP module has shown stable and precise operation on a dummy model with single incision and demonstrated laparoscopic simulation with dexterity.

4.9 Soft machine table

Soft robotic systems are in evolutionary phase; however, they have already exhibited strength to be employed for industrial grade applications. One such demonstration is a soft machine table which has been realized by University of Auckland. This soft table is inspired by the locomotion of caterpillar, which is capable of handling delicate objects (Deng *et al.* 2016). The table can maneuver the objects which are placed on it, with a novel scheme of inverted caterpillar locomotion pattern. The table has soft inflatable chambers network at the top. When these chambers are pneumatically actuated, the produced deformation in a certain sequence displaces the object present on the table surface. The soft table top is prepared by employing Ecoflex 00-30, through molding to develop soft model. The developed soft modules are supported by the main molding case, forming a matrix of such modules to realize the soft table top. This system has effectively demonstrates the capacity of the soft robotic systems for industrial solicitations.

4.10 Soft robotic tongue

A soft robotic tongue for a robotic chewer has been developed to perform the swallowing action like a human chewing mechanism (Lu *et al.* 2017). This pneumatically actuated soft tongue has been fabricated though 3d printed molds using Ecoflex and PDMS materials. The tongue is capable of five movements when it is deformed under the actuation of internal embedded chambers. PneuNet structured chambers in the outer or covering layers of Ecoflex, in combination to the extensible central layer of PDMS, generate motions including roll-up, roll-down, elongation, groove, and twist. This development is a perfect example of the strength of soft robotics being capable to realize bio-inspired systems for operational applications.

5. Discussion

The survey of the literature presented here has been restricted to fundamental developments in the modern era of soft robotics to depict the notion and expedition of this enthusiastic innovative field of robotics. Currently, there are many research organizations, institutes and groups are excelling expeditiously, developing new bio mimicking designs for a variety of applications.

It is evident from previous sections that the implementation of various novel techniques, exploration of appropriate materials, and efforts that are being made towards designing of soft sensors and actuators describe the functional importance of bio-inspired soft robotic systems. This fascination has steered some high-tech developments in this field. From McKibben based systems to FMA structures, and tendon driven to SMA based designs, substantial contributions have been made to imitate natural living beings.

Some of the earliest developments have described the relationship amongst the material properties and the respective conceivable compliance. These initial efforts appraised that it is pertinent to use soft materials for the structural development of the robotic systems to achieve higher compliance. Compliance can be controlled by regulating the feedback gain; and the compliance control enhances the stiffness of soft mechanisms for desired manipulation. Predicting robotic behavior based on material and corresponding actuation pressure can be used for soft robots' gait and position control. Non-linear actuation behavior suggests the development of predictive modeling techniques to effectively develop nonlinear motion control system for soft robots.

Another major orientation of soft robotics is to develop robots capable of generating unstructured motions as service tasks in daily life are quite unstructured in nature. Dexterity along with compliance makes the system more suitable for unstructured environments. Dexterity in soft robots, for instance in human fingers that has always been an inspiration and challenge for scientists, serves to handle thin and fragile items. Again, material and actuation technique plays very important role in achieving such characteristics.

Rubber actuators, the embodiment of most of the soft robots, are quite suitable not only for normal environment but under water as well owing to the water resistance, smooth deformation in compliance to water, high power density and lighter weight. Good performance underwater is one of the main catch imitating different aquatic species. The most inspirational living mechanism for soft roboticists that has multidirectional and multipoint bending, soft and deformable body that can stiffen itself, and has good strength of gripping as well, is the octopus. Different soft mechanisms have been developed based on octopus arm morphology, using different techniques in recent years. Mechanical skills have been evaluated that led to selection of suitable materials and actuation strategies to develop replicated robotic systems. Direct and inverse kinetic models for the control of arm helped to achieve good degree of accuracy demonstrating strength of manipulating algorithm. Successful grasping and manipulation of different shapes, sizes and weights have been demonstrated in these efforts. These systems include tendon driven, muscular hydrostat, PAM based and granular jamming based actuators in combination with especially designed fluidic actuation mechanisms. These efforts clearly indicate the importance of careful selection of the material, actuation scheme and control strategy to successfully robotizing a biologically inspired system.

6. Conclusions

Soft robotics is a perfect prospect towards the realization and development of safe, flexible and compliant robotic systems. Together with bio-inspiration, it has inaugurated the era of biological duos. Underlying actuation principles of biological systems are being evaluated and respective robotics implementations are underway. Silicone is serving as the basic material for most developed soft mechanisms. EAPs, PAMs, SMAs and other applied structural materials have been successfully exploited to demonstrate the potential of these materials and the invented mechanisms. Actuation techniques are being fused to achieve optimal manipulation. Evident efforts have been started towards the development of soft sensors for soft robotic systems.

Soft robotics is in the early phase of its exploration and investigations, and still facing fundamental challenges that any new technology would face. Different materials, actuation techniques, actuators and sensors upgrading, and suitable power sources are being evaluated for designing targeted projects and explicitly project based developments. Perhaps, this would be a key challenge to generalize actuation principles, sensing techniques and material selection that would fit for the development of new soft robots. Another contest in this innovative paradigm is to optimize flexibility and compliance of a developed system. For this purpose, diverse control strategies may require to be explored and examined. Nonetheless, materials need enhanced multifunctional properties that can be implemented to reproduce fully functional biological replicas.

Far future research may take a turn towards the successful development of smart materials capable of acting as body and brain of robotic systems. Such materials, with variety of constituent sensing and actuating properties may be serving as links, joints, skin and other organs of robots. Although the ongoing research is considering imitating underlying principles of biological systems, the future soft robots should be capable of replicating the physical systems in order to take optimal advantage of the natural flexibility and compliance. This would be possible through development of muscles based on smart materials. Furthermore, smart and embedded power sources are to be explored to make the soft robots fully autonomous. Smart materials, in combination with muscles and embedded power sources would make it possible to develop efficient ground, water and flying robots. That would further make it possible to realize proficient service, rehabilitation, prosthetics and industrial robotic manipulators and grippers.

Voyage of facilitating humans with machines, that fostered transforming machines into contemporary robotic systems, has now taken a turn towards imitating biological systems enchanting their softness and compliance. Modern industrial robots have demonstrated their affluent capacity through modern industrial setups in various sectors. Mechanics of rigid configurations and their respective control methods have achieved a level of dexterity today that has made such systems commendable. The idea of soft robotics in its current shape, in the first place, is based on discarding rigid mechanical linkages and joints. This notion leads to a situation that put aside the design strategies of rigid robots and demands a whole new set of mechanics and control for soft materials which should now be forming all essential elements of a robotic system. A fundamental question that can define this need, and is worth answering, is "what kind of a system should be considered as a soft robot?". Is the inspiration of biological systems to develop flexible structures is enough to call a mimicry a soft robot? Is the implementation of underlying actuation principle of a biological system make a robot soft or is it necessary to define the features of soft actuation and essential elements of a soft robot? The future of soft robots is also critically based on whether the soft robotics in its current state is an inspiration to craft biological mockups, or it is just making an impression to create elegant devices covered with soft materials.

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References

Akella, P. and Cutkosky, M. (1989), "Manipulating with soft fingers: Modeling contacts and dynamics", *Proceedings of the 1989 IEEE International Conference on Robotics and Automation*, Scottsdale, Arizona, U.S.A., May.

Alford, W., Wilkes, D., Kawamura, K. and Pack, R. (1997), "Flexible human integration for holonic manufacturing systems", *Proceedings of the World Manufacturing Congress*, Auckland, New Zealand, November.

Anon. (2010), *Athlete Robot*, < http://www.isi.imi.i.utokyo.ac.jp/~niiyama/projects/proj_athlete_en.html>.

Βακουφτσής, K. (2014), *Το πρώτο ρομπότ στην ιστορία της ανθρωπότητας*, *The First Robot, Created in 400 BCE, Was a Steam-Powered Pigeon*, <https://kostasvakouftsis.blogspot.it/2014/04/first-robot-created-in-400-bce-was.html>.

Bao, G., Cai, S., Wang, Z., Xu S.S., Huang, P., Yang, Q., Xu, F. and Zhang, L. (2013), "Flexible pneumatic robotic actuator FPA and its applications", *Proceedings of the International Conference on Robotics and Biomimetics (ROBIO)*, Shenzhen, China, December.

Bertetto, A. and Ruggiu, M. (2001), "In-pipe inch-worm pneumatic flexible robot", *Proceedings of the International Conference on Advanced Intelligent Mechatronics*, Como, Italy, July.

Bogue, R. (2016), "Flexible and soft robotic grippers: The key to new markets?", *Ind. Robot*, **43**(3), 258-263.

Bowler, C.J., Caldwell, D.G. and Medrano-Cerda, G.A. (1996), "Pneumatic muscle actuators: Musculature for an anthropomorphic robot arm", *Proceedings of the IEE Colloquium on Actuator Technology: Current Practice and New Developments*, London, U.K., May.

Bubic, F. (1992), *Flexible Robotic Links and Manipulator Trunks Made Thereform*, U.S. Patent No. 5080000, U.S. Patent and Trademark Office, Washington, D.C., U.S.A.

Caines, R.S. (1991), *Robotic Fluid-Actuated Muscle Analogue*, U.S. Patent No.5021064, U.S. Patent and Trademark Office, Washington, D.C., U.S.A.

Calisti, M., Arienti, A., Renda, F., Levy, G., Hochner, B., Mazzolai, B., Dario, P. and Laschi, C. (2012), "Design and development of a soft robot with crawling and grasping capabilities", *Proceedings of the 2012 IEEE International Conference on Robotics and Automation*, Saint Paul, Minnesota, U.S.A., May.

Cambron, M., Peters II, R., Wilkes, D., Christopher, J. and Kawamura, K. (1998), "Human-centered robot design and the problem of grasping", *Proceedings of the 3rd International Conference on Advanced Mechatronics ICAM'98 -Innovative Mechatronics for the 21st Century*, Okayama, Japan, August.

Chou, C.P. and Hannaford, B. (1996), "Measurement and modeling of McKibben pneumatic artificial muscles", *IEEE Trans. Robot. Autom.*, **12**(1), 90-102.

Cianchetti, M. (2013), "The octopus as paradigm for soft robotics", *Proceedings of the 10th International Conference on Ubiquitous Robots and Ambient Intelligence (URAI)*, Jeju, Korea, November.

Cianchetti, M., Arienti, A., Follador, M., Mazzolai, B., Dario, P. and Laschi, C. (2011), "Design concept and validation of a robotic arm inspired by the octopus", *Mater. Sci. Eng. C*, **31**(6), 1230-1239.

Cianchetti, M., Licofonte, A., Follador, M., Rogai, F. and Laschi, C. (2014), "Bioinspired soft actuation system using shape memory alloys", *Actuators*, **3**(4), 226-244.

Cianchetti, M., Mattoli, V., Mazzolai, B., Laschi, C. and Dario, P. (2009), "A new design methodology of electrostrictive actuators for bio-inspired robotics", *Sensor. Actuat. B Chem.*, **142**(1), 288-297.

Cianchetti, M., Ranzani, T., Gerboni, G., Nanayakkara, T., Althoefer, K., Dasgupta, P. and Menciassi, A. (2014), "Soft robotics technologies to address shortcomings in today's minimally invasive surgery: The STIFF-FLOP approach", *Soft Robot.*, **1**(2), 122-131.

Clarke, R. (1993), "Asimov's laws of robotics: Implications for information technology-Part I", *Comput.*, **26**(12), 53-61.

Deng, Z., Stommel, M. and Xu, W. (2016), "A novel soft machine table for manipulation of delicate objects inspired by caterpillar locomotion", *IEEE/ASME Trans. Mechatron.*, **21**(3), 1702-1710.

Feng, G. and Yen, S. (2015), "Micromanipulation tool replaceable soft actuator with gripping force enhancing and output motion converting mechanisms", *Proceedings of the 18th International Conference on Solid-State Sensors, Actuators and Microsystems (TRANSDUCERS)*, Kaoshiung, Taiwan, June.

Follador, M., Cianchetti, M., Arienti, A. and Laschi, C. (2012), "A general method for the design and fabrication of shape memory alloy active spring actuators", *Smart Mater. Struct.*, **21**(11), 115029.

Gellius, A. and Beloe, W. (1795), *The Attic Nights of Aulus Gellius*, J. Johnson, London, U.K.

Giorelli, M., Renda, F., Calisti, M., Arienti, A., Ferri, G. and Laschi, C. (2012), "A two dimensional inverse kinetics model of a cable driven manipulator inspired by the octopus arm", *Proceedings of the 2012 IEEE International Conference on Robotics and Automation*, Saint Paul, Minnesota, U.S.A., May.

Grissom M, D., Chitrakaran, V., Dienno, D., Csencits, M., Pritts, M., Jones, B., McMahan, W., Dawson, D., Rahn, C. and Walker, I. (2006), "Design and experimental testing of the OctArm soft robot manipulator", *Proceedings of the SPIE Defense and Security Symposium*, Orlando, Florida, U.S.A., April.

Groen, F., van der Smagt, P. and Schulten, K. (1996), "Analysis and control of a rubbertuator arm", *Biol. Cybernet.*, **75**(5), 433-440.

Hakozaki, M., Nakamura, K. and Shinoda, H. (1999), "Telemetric artificial skin for soft robot", *Proceedings of the International Conference on Solid State Sensors and Actuators* (*Transducers'99)*, Sendai, Japan, June.

Hamerlain, M. (1995), "An anthropomorphic robot arm driven by artificial muscles using a variable structure control", *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems 95 'Human Robot Interaction and Cooperative Robots'*, Pittsburgh, Pennsylvania, U.S.A., August.

Hoggett, R. (2012), *Artificial Muscle, Joseph Laws McKibben (American)*, <http://cyberneticzoo.com/bionics/1957artificial-muscle-joseph-laws-mckibben-american>.

Iida, F. and Laschi, C. (2011), “Soft robotics: Challenges and perspectives”, *Proc. Comput. Sci.*, **7**, 99-102.

Ilievski, F., Mazzeo, A., Shepherd, R., Chen, X. and Whitesides, G. (2011), “Soft robotics for chemists”, *Angewandte Chemie*, **123**(8), 1930-1935.

Jung, K., Koo, J., Nam, J., Lee, Y. and Choi, H. (2007), “Artificial annelid robot driven by soft actuators”, *Bioinspir. Biomimet.*, **2**(2), S42-S49.

Kang, R., Branson, D., Zheng, T., Guglielmino, E. and Caldwell, D. (2013), “Design, modeling and control of a pneumatically actuated manipulator inspired by biological continuum structures”, *Bioinspir. Biomimet.*, **8**(3), 036008.

Kang, R., Guglielmino, E., Zullo, L., Branson, D., Godage, I. and Caldwell, D. (2016), “Embodiment design of soft continuum robots”, *Adv. Mech. Eng.*, **8**(4), 168781401664330.

Kim, S., Laschi, C. and Trimmer, B. (2013), “Soft robotics: A bioinspired evolution in robotics”, *Trend. Biotechnol.*, **31**(5), 287-294.

Klute, G.K., Czerniecki, J.M. and Hannaford, B. (1999), “McKibben artificial muscles: Pneumatic actuators with biomechanical intelligence”, *Proceedings of the IEEE/ASME International Conference on Advanced Intelligent Mechatronics*, Atlanta, Georgia, U.S.A., September.

Kotsanas.com. (2016), *The Flying Pigeon of Archytas*, <http://kotsanas.com/gb/exh.php?exhibit=2001001>.

Kure, K., Kanda, T., Suzumori, K. and Wakimoto, S. (2008), “Flexible displacement sensor using injected conductive paste”, *Sensor. Actuat. A Phys.*, **143**(2), 272-278.

Laschi, C., Mazzolai, B., Mattoli, V., Cianchetti, M. and Dario, P. (2009), “Design of a biomimetic robotic octopus arm”, *Bioinspir. Biomimet.*, **4**(1), 015006.

Lu, X., Xu, W. and Li, X. (2017), “A soft robotic tongue-mechatronic design and surface reconstruction”, *IEEE/ASME Trans. Mechatron.*, **22**(5), 2102-2110.

Margheri, L., Laschi, C. and Mazzolai, B. (2012), “Soft robotic arm inspired by the octopus: I. From biological functions to artificial requirements”, *Bioinspir. Biomimet.*, **7**(2), 025004.

Mazzolai, B., Margheri, L., Cianchetti, M., Dario, P. and Laschi, C. (2012), “Soft-robotic arm inspired by the octopus: II. From artificial requirements to innovative technological solutions”, *Bioinspir. Biomimet.*, **7**(2), 025005.

McMahan, W., Chitrakaran, V., Csencsits, M., Dawson, D., Walker, I.D., Jones, B.A., Pritts, M., Dienno, D., Grissom, M. and Rahn, C.D. (2006), “Field trials and testing of the OctArm continuum manipulator”, *Proceedings of the 2006 IEEE International Conference on Robotics and Automation*, Orlando, Florida, U.S.A., May.

Noh, Y., Sareh, S., Back, J., Würdemann, H., Ranzani, T., Secco, E., Faragasso, A., Liu, H. and Althoefer, K. (2014), “A three-axial body force sensor for flexible manipulators”, *Proceedings of the 2014 IEEE International Conference on Robotics and Automation*, Hong Kong, China, May-June.

Obaji, M. and Zhang, S. (2013), “Investigation into the force distribution mechanism of a soft robot gripper modeled for picking complex objects using embedded shape memory alloy actuators”, *Proceedings of the 6th IEEE Conference on Robotics, Automation and Mechatronics (RAM)*, Manila, Philippines, November.

Pack, R.T. and Iskarous, M. (1994), “The use of the soft arm for rehabilitation and prosthetic”, *Proceedings of the Annual Conference Rehabilitation Engineering and Assistive Technology Society of North America 1994*, Nashville, Tennessee, U.S.A., June.

Pritts, M.B. and Rahn, C.D. (2004), “Design of an artificial muscle continuum robot”, *Proceedings of the International Conference on Robotics and Automation (ICRA04)*, New Orleans, Louisiana, U.S.A.

Ranzani, T., Cianchetti, M., Gerboni, G., Falco, I. and Menciassi, A. (2016), “A soft modular manipulator for minimally invasive surgery: Design and characterization of a single module”, *IEEE Trans. Robot.*, **32**(1), 187-200.

Renda, F., Cianchetti, M., Giorelli, M., Arienti, A. and Laschi, C. (2012), “A 3D steady-state model of a tendon-driven continuum soft manipulator inspired by the octopus arm”, *Bioinspir. Biomimet.*, **7**(2), 025006.

Rieffel, J., Knox, D., Smith, S. and Trimmer, B. (2014), “Growing and evolving soft robots”, *Artif. Life*, **20**(1), 143-162.

Rus, D. and Tolley, M. (2015), “Design, fabrication and control of soft robots”, *Nature*, **521**(7553), 467-475.

Sasaki, D., Noritsugu, T. and Takaiwa, M. (2005), “Development of active support splint driven by pneumatic soft actuator (ASSIST)”, *Proceedings of the 2005 IEEE International Conference on Robotics and Automation*, Barcelona, Spain, April.

Sasaki, D., Noritsugu, T., Takaiwa, M. and Kataoka, Y. (2005), “Development of pneumatic wearable power assist device for human arm “ASSIST””, *Proceedings of the JFPS International Symposium on Fluid Power*, Tsukuba, Japan, November.

Shepherd, R., Ilievski, F., Choi, W., Morin, S., Stokes, A., Mazzeo, A., Chen, X., Wang, M. and Whitesides, G. (2011), “Multigait soft robot”, *Proc. National Acad. Sci*., **108**(51), 20400-20403.

Shintake, J., Schubert, B., Rosset, S., Shea, H. and Floreano, D. (2015), “Variable stiffness actuator for soft robotics using dielectric elastomer and low-melting-point alloy”, *Proceedings of the International Conference on Intelligent Robots and Systems (IROS)*, Hamburg, Germany, September-October.

Stone, R.S.W. and Brett, P.N. (1995), “A flexible pneumatic actuator for gripping soft irregular shaped objects”, *Proceedings of the IEE Colloquium on Innovative Actuators for Mechatronic Systems*, London, U.K., October.

Suzumori, K. (1989), “Flexible microactuator (1st Report, Static characteristics of 3 DOF actuator)”, *Trans. Jap. Soc. Mech. Eng. Series C*, **55**(518), 2547-2552.

Suzumori, K. (1990), “Flexible microactuator. (2nd Report, Dynamic characteristics of 3 DOF actuator)”, *Trans. Jap. Soc. Mech. Eng. Series C*, **56**(527), 1887-1893.

Suzumori, K. (1996), “Elastic materials producing compliant robots”, *Robot. Autonom. Syst*., **18**(1-2), 135-140.

Suzumori, K., Endo, S., Kanda, T., Kato, N. and Suzuki, H. (2007), “A bending pneumatic rubber actuator realizing soft-bodied manta swimming robot”, *Proceedings of the 2007 IEEE International Conference on Robotics and Automation*, Rome, Italy, April.

Suzumori, K., Iikura, S. and Tanaka, H. (1991), “Development of flexible microactuator and its applications to robotic mechanisms”, *Proceedings of the 1991 IEEE International Conference on Robotics and Automation*, Sacramento, California, U.S.A., April.

Suzumori, K., Iikura, S. and Tanaka, H. (1991), “Flexible microactuator for miniature robots”, *Proceedings of the Micro Electro Mechanical Systems, MEMS’91, An Investigation of Micro Structures, Sensors, Actuators, Machines and Robots*, Nara, Japan, January.

Suzumori, K., Iikura, S. and Tanaka, H. (1992), “Applying a flexible microactuator to robotic mechanisms”, *IEEE Control Syst*., **12**(1), 21-27.

Suzumori, K., Koga, A. and Haneda, R. (1994), “Microfabrication of integrated fmas using stereo lithography”, *Proceedings of the IEEE Workshop on Micro Electro Mechanical Systems, MEMS’94*, Oiso, Japan, January.

Suzumori, K., Koga, A., Kondo, F. and Haneda, R. (1996), “Integrated flexible microactuator systems”, *Robotica*, **14**(5), 493-498.

Suzumori, K., Kondo, F. and Tanaka, H. (1993), “Micro-walking robot driven by flexible microactuator”, *J. Robot. Mechatron*., **5**(6), 537-541

Suzumori, K., Maeda, T., Wantabe, H. and Hisada, T. (1997), “Fiberless flexible microactuator designed by finite-element method”, *IEEE/ASME Trans. Mechatron*., **2**(4), 281-286.

Suzumori, K., Miyagawa, T., Kimura, M. and Hasegawa, Y. (1999), “Micro inspection robot for 1-in pipes”, *IEEE/ASME Trans. Mechatron*., **4**(3), 286-292.

Takashi, Y., Naoyuki, I., Makoto, M. and Yoshinobu, A. (2012), “Picking up operation of thin objects by robot arm with two-fingered parallel soft gripper”, *Proceedings of the 2012 IEEE Workshop on Advanced Robotics and its Social Impacts (ARSO)*, Munich, Germany, May.

Toshiba.co.jp. (1997), *Toshiba: Press Releases 21 February, 1997*, <https://www.toshiba.co.jp/about/press/1997_02/pr2101.htm>.

Trimmer, B.A., Lin, H.T., Baryshyan, A., Leisk, G.G. and Kaplan, D.L. (2012), “Towards a biomorphic soft robot: Design constraints and solutions”, *Proceedings of the 4th IEEE RAS & EMBS International Conference on Biomedical Robotics and Biomechatronics (BioRob)*, Rome, Italy, June.

Trivedi, D. and Rahn, C. (2014), "Model-based shape estimation for soft robotic manipulators: The planar case", *J. Mech. Robot.*, **6**(2), 021005.
Trivedi, D., Dienno, D. and Rahn, C. (2008a), "Optimal, model-based design of soft robotic manipulators", *J. Mech. Des.*, **130**(9), 091402.
Trivedi, D., Lotfi, A. and Rahn, C. (2008b), "Geometrically exact models for soft robotic manipulators", *IEEE T. Robot.*, **24**(4), 773-780.
Udupa, G., Sreedharan, P. and Aditya, K. (2010), "Robotic gripper driven by flexible microactuator based on an innovative technique", *Proceedings of the 2010 IEEE Workshop on Advanced Robotics and its Social Impacts (ARSO)*, Seoul, South Korea, October.
Wilkes, D., Pack, R., Alford, A. and Kawamura, K. (1997), *A Design Philosophy for Socially Intelligent Service Robots*, in *American Association for Artificial Intelligence*, AAAI Press Technical Report FS-97-02, AAAI Press, 140-145.
Yamaha, Y., Iwanaga, Y., Fukunaga, M., Fujimoto, N., Ohta, E., Morizono, T. and Umetani, Y. (1999), "Soft viscoelastic robot skin capable of accurately sensing contact location of objects", *Proceedings of the* 1999 *IEEE/SICE/RSJ International Conference on Multisensor Fusion and Integration for Intelligent Systems(MFI'99)*, Taipei, Taiwan, August.
Yamamoto, Y., Kure, K., Iwai, T., Kanda, T. and Suzumori, K. (2007), "Flexible displacement sensor using piezoelectric polymer for intelligent FMA", *Proceedings of the 2007 IEEE/RSJ International Conference on Intelligent Robots and Systems(IROS2007)*, San Diego, California, U.S.A., October-November.

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