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SOFT ROBOTICS WITH COMPLIANCE AND ADAPTATION FOR BIOMEDICAL APPLICATIONS AND FORTHCOMING CHALLENGES

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Abstract

Biology has always motivated engineers to come up with efficient and reliable machines to move in complex environments. The dexterity, softness, and body compliance of natural system such as cephalopods or caterpillars have inspired robotic engineers to incorporate soft, deformable materials such as gels and elastomers into their designs. Hence, the inception of soft robots shifts the paradigm and trends in robotics, which could potentially revolutionize health care, human–robot interaction, field exploration, rehabilitation, and related applications. Throughout this review article, we have restricted our discussion to the applications of soft robots in biomedical domains exclusively and the perennial challenges faced therein.

Key Words

Soft robots, dexterity, softness, body compliance, elastomer, health care

1. Introduction

Mainstream robots are made of rigid materials that resist elastic deformations. Rigid, hard, and inflexible robots can be precise and powerful, but they lack the multi-functionality of natural organisms [1]. As the field of robotics expands and evolves beyond the boundary of manufacturing and industrial automation towards health care, field exploration, and human–robot collaboration, the involved agents are less rigid and more open to specialized mechanical compliance. A new paradigm of robotics called "soft robotics" has evolved to incorporate human–robot interaction into the biomedical robotics realm.

In Fig. 1, elastic properties, yield point behaviour, and plastic deformation of various classes of materials are portayed, and the gap between rigid and soft material is outlayed clearly. As per the description depicted in Fig. 1, soft materials such as human skin and cartilage possess Young's moduli, E, of much smaller magnitude ($E \sim 10^4$–10^9 Pa) than rigid materials ($E \sim 10^9$–10^{12} Pa) such as metals and hard plastics. Characterizing the transition from hard to soft material and *vice versa* is crucial, as almost all

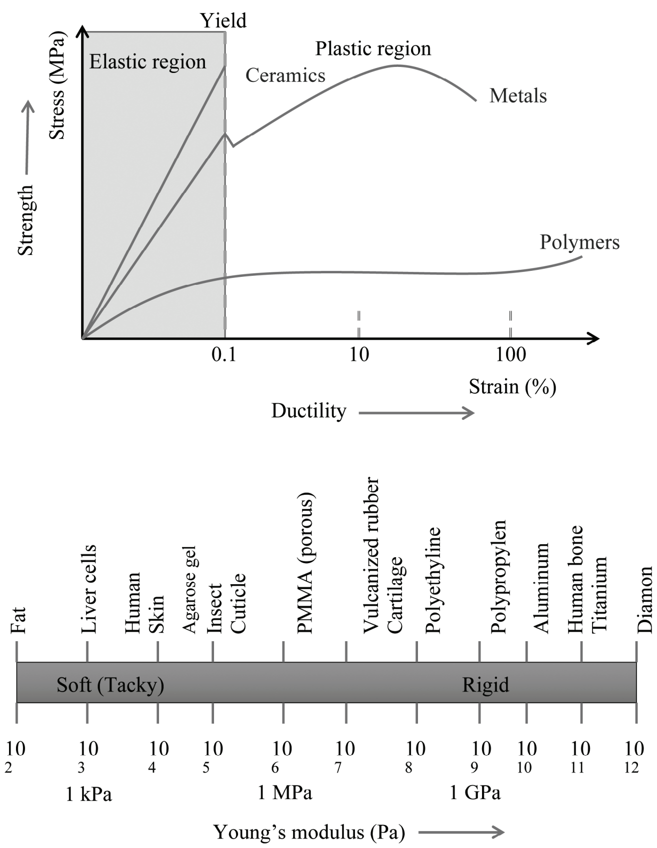

Figure 1. The transition from soft to rigid materials by Young's modulus [3].

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living organisms come with a combination of both however with an exception to many invertebrates that do not have skeleton and can live perfectly fine. Therefore, there is some benefit on mixing hard and soft components, when completely soft and completely hard structures are good to complementarily accomplish different kind of goals. A clear understanding of biological soft actuation mechanisms that function in a complex environment can undoubtedly provide indispensable knowledge to further the application of soft robotics to rescue operations, disaster management, health care, human assistance, *etc.* [2].

Compared to rigid bodied robots; soft robots are continually deformable, resilient, and possess relatively high compliance [4]–[6]. These characteristics provide soft robots an incredible agility to adapt to new environments and move through narrow places. They can also collect and send valuable information to humans in highly sophisticated biomedical applications and rescue operations. Though soft robots provide a huge range of possibility in the future of bio-inspired robotics, this technology comes with its own set of challenges as well. For example, it is challenging to design flexible actuation systems capable of high forces that replicate the functionality of muscles in the animal body. Soft robotics systems can be complex because the ability of soft animals to change body shape depends on a number of muscles distributed over the body.

In this article, we have focused our discussion about soft robots applied to the biomedical field and the associated challenges including actuation, fabrication, design, and control. Through the initial parts of our paper, we delved in soft robotics application towards promising medical fields while towards the end we touch upon the persisting grand challenges with a possible solution for a better human–machine social interaction.

2. Biological Inspiration

The significant role that natural organisms have played over time in motivating engineers to make ever more capable machines for various applications is truly fascinating [7], [8]. There are many lessons learned from biological systems such as distributing stress throughout body and adapting to a rapidly changing environments, which have been used to improve soft, flexible robots. These soft bodied machines have special advantages of softness and body compliance over the rigid links and joints offered by their rigid-body robot counterparts [9]. Most rigid-bodied robots are unsafe for interacting with humans, making them undesirable for human-in-the-loop cooperative operations. On the other hand, soft robots have unprecedented adaption, compliance, and flexibility [2] to deform continuously with high degrees of freedom (DOFs) [8].

There are innumerable examples of soft, mobile structures in nature, which can be successfully implemented in man-made structures. A muscular hydrostat is a biological structure that can bend, twist, and extend easily [4]. Soft invertebrates such as squid, jellyfish, and giant earthworms deform their bodies simultaneously for adaptation with the surrounding medium and better access to food and shelter. Many researchers are focusing their studies on octopuses, which extend their limbs quite quickly [10] especially when striking their prey [11]. The fundamental understanding of morphology and structures of these arthropods and invertebrates will help developers create novel, robust soft robot designs [12]–[14].

3. Soft Robotics in Biomedical Applications

Fabrication of soft robots requires materials such as gels and elastomers that are generally classified as organic materials and assumed to be biocompatible in nature. Thus, the inherent characteristics of soft robotics make them useful for a range of biomedical applications such as surgical manipulators, wearable robots for human–motor interactions, cooperative robots for safety interactions, and many others. Over the last few decades, rapid advances in synthetic biology have created a huge demand for scientists to incorporate research discoveries into the creation of the next generation of biomaterials. Biomaterials research is important for uncovering novel materials for soft, flexible robots to be used in medical care. There are already thousands of biological substances such as fats, proteins, and sugars, which can readily be used for structural components of biodegradable, biocompatible, environmentally friendly soft robotics applications [15]. Here, we have delved into the domain of biomedical engineering and highlighted some emerging biomedical applications, which will push scientists to overhaul the way we think about robotics.

3.1 Soft, Flexible Robotic Surgery: A New Paradigm of Soft Robotics

To overcome long persisting limitations in current surgical instrumentations, minimally invasive robotic surgical systems aim at providing remote tele-operated diagnosis and treatment through small incisions with their slim and dexterous robotic manipulators. Currently, robotic engineers try to emulate design principles from biology when creating novel medical devices. With the overarching progress in surgical robotics depicted in Fig. 2, it is clear that there has been a longstanding need in minimally invasive surgery (MIS) for surgical tools that can go through narrow gaps, interact with soft organs, and move, deform, or change stiffness. Drawing upon biology, scientists design a novel variable stiffness manipulator for surgery [16]. Soft, dexterous, and highly flexible surgical manipulators are ideal for MIS applications because they are: (i) able to squeeze through small incisions gaps, (ii) inherently soft and compliant because of their similar stiffness (Young's modulus) to human soft tissues, (iii) easy to scale and modularize, (iv) low cost due to the easily available low-cost soft materials, (v) biocompatible, and (vi) disposable.

Here, we list the reported surgical platforms developed based on soft, flexible, dexterous robotics, which have the potential to completely change surgical procedures.

3.1.1 Soft Flexible and Learnable Surgical Manipulators

Integrating lessons learned from biology, cognitive science, robotics, and medical sciences can reform the way we look

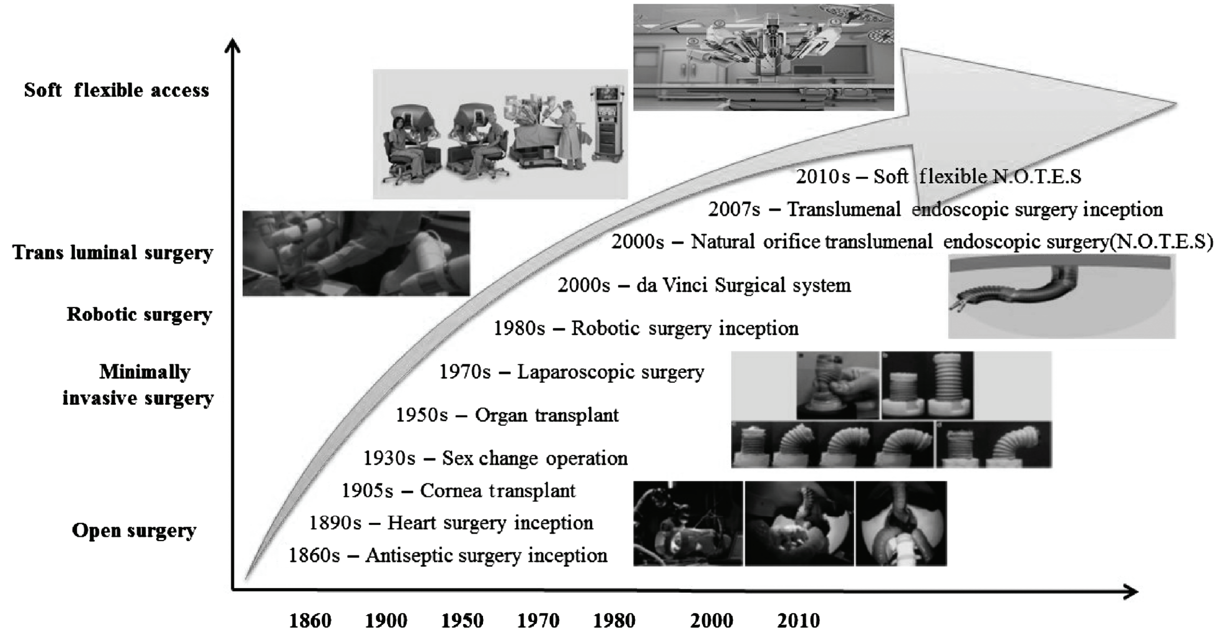

Figure 2. Milestones of surgery and its evolution [16], [17].

surgery through MIS. Next generation manipulators intended for surgery should be thin, flexible, and/or soft so they can squeeze through narrow channels and function in tight, remote body areas that are difficult for surgeons to access with conventional medical manipulators. A modular and curvilinear structure arm called STIFF-FLOP was proposed to safely monitor with surgical environment through compliance and flexibility [17]–[19]. To enhance more robust and optimal solutions of STIFF-FLOP method, an analytical technique with experimental validation has been conducted by a team of researchers, which can pave the way for flexible surgical tool development much faster [20]. As demonstrated in Fig. 3 the proposed variable stiffness robot arm can have the potential to be applied not only to MIS (*e.g.*, endoluminal surgery, NOTES) but also to activities including bomb defusing, disaster management, rescue operations, and inspection of complex engineering systems (Fig. 3).

Biologically inspired robotics enhances the use of flexible modular surgical tools so that it provides a much smoother life for surgeon and patient. For example, octopus tentacles motivated engineers to come up with novel solutions for developing the surgical tools [21]. A revised kinematic model was proposed here, and a cable-driven soft manipulator was designed for testing in live animal heart ablation. Mortality and morbidity are some important governing factors in cases of pancreatic cancer and chances of failure in laparoscopic pancreaticoduodenectomy are not out of scope due to sharp, rigid nature of forceps and surgical tools. To counteract this, a shape deposition manufacturing technique was used for soft, flexible, deployable atraumatic graspers in surgery [22]. A 3D-printed soft cable-driven manipulator combined with MRI for improved neurosurgery to remove brain tumors [23]. A micro pneumatic actuator was developed that can bend up to 115° due to the mechanical properties of PDMS and Ecoflex [24]. Surgical techniques are advancing steadily into the realm of soft robotics for MIS with high accuracy, precision, and safety.

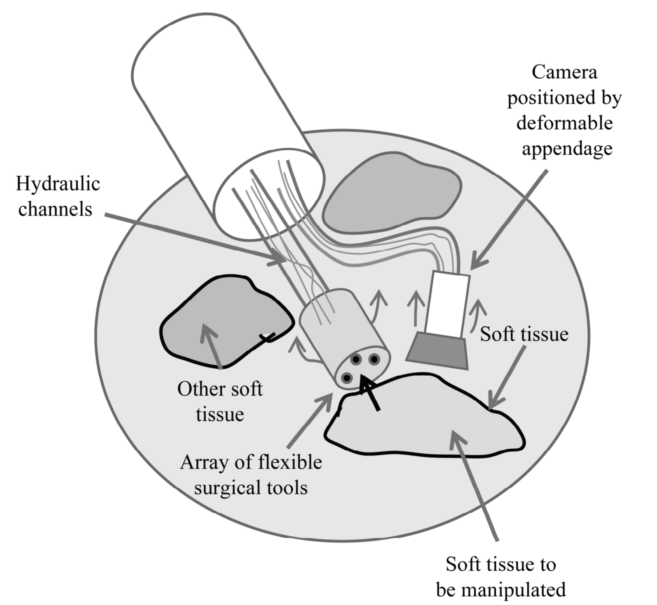

Figure 3. Schematic of a flexible surgical manipulator [19].

3.2 Soft Robots in Rehabilitation

Robots promise a positive shift in the field of physical rehabilitation. During last two decades, there has been a sharp increase of researchers working towards rehabilitation robotics therapy for patients with motor disease caused by stroke and spinal cord conditions [25]. Instead of hard, non-dexterous robots, researches are currently shifting more towards soft wearable robots, which can safely interact with people [26]. As an example in the domain of co-robotics, a soft active ankle-foot orthotic can be useful to prevent foot dragging for gait abnormality patients [27].

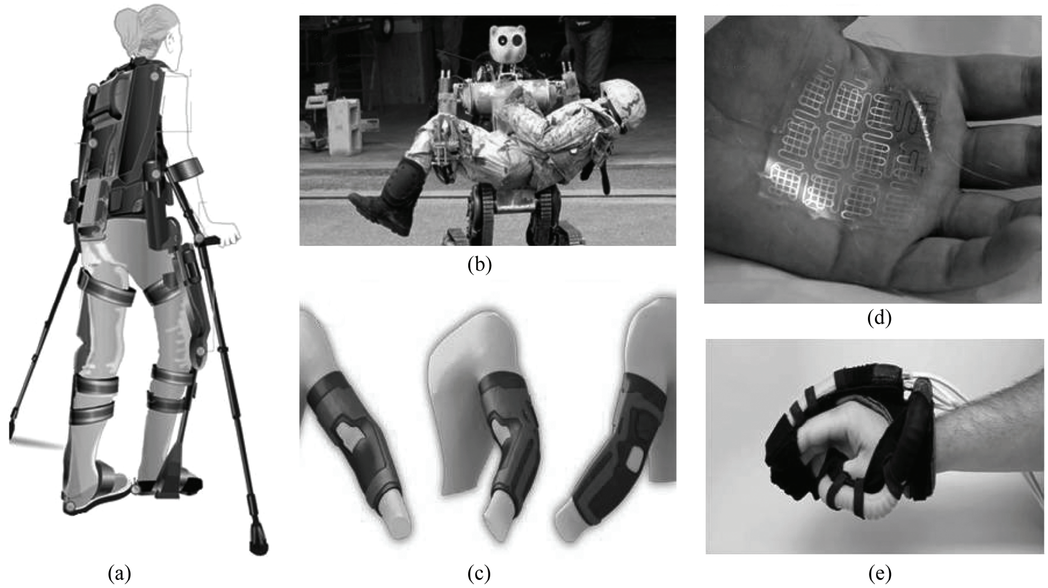

Figure 4. Robot-assisted rehabilitation: (a) exoskeleton – the bionic walker; (b) humanoid co-robot for elderly care, rescue operation, and disaster management; (c) "second skin" for human motor interaction; (d) wearable keyboards; (e) soft glove for rehabilitation [32]–[35].

Soft wearable robots are also promising for improving the life of patients suffering from stroke or brain injuries by providing assistance with grasping and other motor tasks. Soft hand orthotic robots can perform a task as artificial muscle popularly named as *second skin* [28], which compensates body's impaired motor function cooperating with healthy tissue [25].

3.2.1 Soft Wearable Device

A single flexible sensor is been set to include soft wearable input device, which has put the robotic community even closer to achieving skin-like tactile sensing. Soft robotics combine flexibility and elasticity, puts to a new promising horizon of wearable sensors and tactile interfaces that calls for stretching several times and yet functional [29]–[31]. To extend the possibility of soft wearable electronics further, a nice, lucid example of thin, transparent elastomeric sheet embed with conductive liquid micro channels for wearable keyboards [32]. On the other hand, an active soft orthotic device is developed to ameliorate neuromuscular disorder [33]. As demonstrated in Fig. 4 wearable soft robots are a new genre in the soft wearable medical device platform, and they come with their own challenges in design and fabrication posed by actuation, sensing, and control (as illustrated in [34] for lower limb measurement of human body) (Fig. 4).

3.3 Tissue Engineering: Artificial Skin/Nervous Tissue

Soft elastomeric materials provide a new platform for bioengineered hybrid devices [36]. There is a widely accepted report of creating a flexible biohybrid microsystem, which mimics the human lung alveolus-capillary interface [37]. For reproducing the clinical mechanical effect of breathing, researchers have published a tissue-engineered jellyfish, which can swim by growing cardiac muscle cells [38]. As we discussed previously, biomaterials are frequently used for MIS, and the tissue growth is made from biopolymers scaffolding, *e.g.*, silk [39]. Studies have shown that soft robots can be designed with biomaterials that are capable of delivering drugs locally [40] or even depositing materials, which can be used as a scaffold for tissue engineering [41]. There are instances where soft robotics fabrication goes far beyond traditional tissue engineering – with current techniques, muscle cells can be grown as a 3D printed hydrogel structure [42]. Recently, researchers at National University of Singapore (NUS) reported that their development of a millimeter size soft pneumatic actuator (SPA) for enclosing sciatic nerve of rat, promising a nice platform for future biological soft tissue research. The research was followed by a novel, highly scalable, shape engineering fabrication method and supported by a modeling and characterization approach. This work paved the way for future research in shape engineering by using mathematical modeling to achieve higher sophistication and wider range of sub-millimeter scale biomimetic applications [43].

Soft robots built from biological materials and living cells inherit the advantages of these materials: they have extraordinary potential for self-assembly (from molecular structures to integrated devices); they are powered by energy-dense, safe, hydrocarbons such as lipids and sugars; and they are biocompatible and biodegradable, making them a potentially green technology. The primary robotic components needed are: (i) actuators (synthetic or living muscles); (ii) a mobile body structure (built from biopolymers in any desired configuration); and (iii) a supply of biofuel (*e.g.*, mobilizing glucose or lipid reserves in the body cells of the robot). Such robots could be built (or grown) by using parallel fabrication methods; therefore, they also have great potential for tasks that require disposable devices or swarm-like interactions. New challenges lie in the selection of appropriate tissue sources and in interfacing them with synthetic materials and electronics.

3.4 Bio-microfluidics Applications

Microfluidic technology poses a new paradigm shift in biomedical cell biology *in vitro* research as microfluidic channels are assumed to mimic largely the confinement effect introduced by micro confinement of physiological pathways [44]. Recently, researchers have been using microfluidic channels to fabricate soft robots that mimic biological networks. As an example, this microfluidics technique is combined with pattern and color to provide camouflage display of soft robots that mimic the cephalopod's appearance [45]. There are numerous other occasions where researches used soft lithography techniques adapted from microfluidics to design effective pneumatic actuators rooted with paper or cloth for soft biological machines [46]–[48]. In the near future, soft microfluidic circuit fabrication from photolithography will advance the design of pumps, valves, and relays to support the emerging field of novel actuation and stretchable electronics that will reinforce the field of soft-matter engineering further [1].

4. Challenges in Soft Robotics

4.1 Soft Material and Polymers: Design and Fabrication Challenges

The transition from a hard conventional robot to its soft counterpart depends on its underlying materials [4]. The materials, and spatial orientation of the materials, used for soft robots allow for deformable, dexterous, soft interfaces, but the fabrication process poses a challenge for robotic engineers. Currently, soft robotic researchers frequently use state of the art 3D printing and soft lithography fabrication techniques [49]–[52], stretchable electronics with wavy circuits [53], [54], soft microfluidic channel with conductive liquid [55], highly stretchable smart textiles, wearable computing, *etc.*

The next challenge is to 3D print active, multi-material components into a single packet for final use [56]–[58]. Though this 3D print technology, revolution puts a milestone in the scientific community, it should be mentioned that unlike conventional rigid robots, soft robots require design and manufacturing from scratch, which makes knowledge transfer critical. For example, there are very few well-characterized soft materials that can be used extensively for the 3D printing – therefore, the field of soft robotics is a fertile land for future chemists to discover new polymers. To make this polymers work for a suitable desired task in most optimum manner, a well qualitative direct actuation performance comparison is a must choice. In Table 1, we unveil the classification of actuation methods with traditional approaches such as motors and cables for the sake of completeness.

4.2 Computation and Control Challenges

In comparison to rigid, inflexible, conventional robots, soft robots theoretically possess infinite DOFs making control extremely challenging. The materials used for soft robotics are generally non-linear in nature, which makes it exceedingly difficult to predict the empirical coefficient that can mimic the experimental non-linear elastic behaviour, damping coefficients, interfaces between materials, and friction [65]. As soft materials are continuous and deformable [66], the optimal control of the new generation of soft robots needs the state variables of body posture, which are missing as the design parameters are continually changing with deformations, and difficult to address with classical mechanics. The computations become even more difficult if the actuator is to generate optimum force and torque for a desired application. For example, electroactive polymers require very high voltage (in kV range) to operate, while low voltage ionic polymer metal composites are insufficient to generate enough force and thrust. Pneumatic actuators need an extensive additional pressure infrastructure, while shape-memory alloy (SMAs) has serious trouble with overheating and surface damage.

There is ongoing research in simulating continually deformable, highly compliant, flexible bodies using piecewise constant curvature (PCC) model [67], Bernoulli–Euler beam mechanics [68] for deformation prediction, or inverse kinematic algorithm. Each of these standard approaches to modelling bio-inspired robotic systems comes with its own challenges. For example, PCC does not necessarily guarantee to incorporate all characteristics of soft robots, for which non constant curvature model is being introduced recently [69]. On the other hand, inverse kinematics does not include the whole soft body, and even the end effectors poses are not included in solutions. To illustrate additional state of the art simulation and control approaches in the soft robotics field, we have listed in Table 2 some interesting recent articles (from the year 2010 onwards) and challenges faced therein. Though dynamic modelling somewhat mimics the high deformation of soft materials, interfacing control will be a great challenge as it requires a model-based prediction. So as dynamic modelling progresses, there is a great need to update control algorithms to fit real-time, complex situations.

4.3 Commercial Challenges

Soft robots have great potential to be applied in industrial automation and health care realms. As per the prediction projected by ABI research, the market of personal robots may undergo a sharp fall from previous estimates to \$6.5 billion by 2017 [85], which leaves engineers no choice but to focus more on cost-effective, flexible, soft robots. But, this emerging technology has many challenges to overcome before it can be widely commercialized. First, it is extremely difficult for start-ups to sell directly to end users or to collaborate with large manufacturers as they typically want to partner up with companies which already demonstrate an operational track record and financial

Table 1
Type of Actuations and Their Advantages and Challenges [17] [59]–[64]

Type of Actuations	Materials of Use	Operating Physics	Stress	Strain	Power Density	Scaling Dimensions	Response Velocity	Advantages	Challenges
Motor	Metals/alloys	Cables pulling for flexible bending	M/L	High (H)	Medium (M)	Low (L)	H	Ease in assembly/ disassembly, light moving components and low cost	Non-linear behavior, unidirectional constraint that can only pull and not push, undesirable disturbances lead whole system uncontrollable
Shape-memory alloy (SMA)	Copper-aluminum-nickel and nickel-titanium (NiTi)	Electrical current induced Joule heating	Wires: high Springs: medium/ low	M	H	H	L	High mass specific force	Relatively low (nearly 5%) strain, force generation in SMAs depends on temperature change, overheating or overstraining can cause permanent damage to the actuator
Shape-memory polymer (SMP)	Ploy(urethane)-based thermoplastic	Polymer	M	M	M/L	H	L	Less weight per unit volume of material, reversible change of elastic modulus, ease of processibility, lower cost	Low modulus
Dielectric elastomeric actuators (DEA)	Silicone and acrylic elastomers	Electrostatic force of application	M	H	M/L	M/L	H	High strain/stress and mass specific power	Requires a rigid frame for prestrains the elastomer, reliability of the compliant electrodes needs improvement. DEAs actuation requires high voltage
McKibben pneumatic artificial muscles	Fiber braid	Gas chambers	M	H	M/H	M/L, mainly because of the pneumatic pumps	H	Soft fabrication, quick actuation, easily integrated into three dimensional soft actuated materials	To achieve relatively high forces and displacements they required high power and complex compressed air supply systems, friction between bladder and the mesh also contributes to actuator hysteresis
Fluidic elastomeric actuator (FEAs)	Synthetic elastomeric films	Chamber network	H	H	H	M/L	M/H	Operated both pneumatically or hydraulically, versatile fabrication approaches to embed fibers	Slow actions

stability. Second, even if there is financial support for R&D and marketing activities, obtaining regulatory approval for medical applications takes a long time (5–10 years), which means investors need to commit to financial support for a long period of time.

There is no doubt that in the near future, market demand will influence the commercialization of soft wearable machines and medical robotics. Apart from manufacturing scalability, consumer interests, and efficient and viable technical solutions, “soft robots” will face great pressure to be inexpensive and optimized to meet the steep market demand. The great advancement of electronics integrated chip (IC) and microfluidics network in the last few decades follow Moore’s Law nicely, while soft robots have yet to climb that ladder and face great challenges in the future. However, according to Bank of America Merrill Lynch research, medical robots business is expected to grow at a much faster rate to reach $18b by 2022 even though compared to industrial robots, medical robots adoption is still at an early stage, with 1,224 units sold for $1.3b in 2014, only accounting for 5% of total robots sold [86]. On a final note to sum up, Prof. George Whitesides – in an interview with Prof. Barry Trimmer – clearly explained that the field of “soft robot” actuators is still in its nascent phase and will be commercially challenging for researches to explore in the near future [87].

Table 2
Existing Literature for Bioinspired Soft Robots with Modelling and Control Approaches

Short Summary	Biomedical Applications	Type of Actuation	Fabrication Material	Mathematical Modelling	DOF	Striking Results	Challenges to Overcome	Lead Author (Year of Publication)	Reference
Soft robotic grippers on deep reefs	Nondestructive sampling of benthic fauna	Fiber-reinforced bellow-type actuators	Smooth-Sil 950 Smooth On	No	Five	First step towards being used as human SCUBA diver	Fabrication and design for the study of marine applications	Galloway (2016)	[70]
Diversified soft pneumatic actuators (SPA)	Soft biological tissue engineering	Pneumatic	PDMS	Inflation model of the arc	–	Bending radius follows an inversely proportional trend with input air pressure	Modelling aspect for higher sophistication and functionality	Liang (2016)	[43]
Human compliant soft robotic ultrasound imaging	Noninvasive real time ultrasound imaging of targeted organ without any human intervention	Pneumatic	Liquid silicon (Eco-Flex 0030)	No	Three	Bending angle of SPA varies in some proportional ratio with the increasing air actuated pressure	Optimization and control with mathematical modelling	Ren (2016)	[71]
Improving soft pneumatic actuator fingers	Robot fingers to grasp, control, and monitor soft biological tissues	Pneumatic	Eutectic Indium Gallium alloy (EGaIn) sensors	Piecewise linear model	–	Several fingernails outperformed the bare finger when grasping objects off a flat surface, PID and feed forward can accurately control position and force	Optimization and controlled soft pneumatic actuators (SPAs) for lifting heavy body	Morrow (2016)	[72]
Miniature soft flexible robotic manipulator	Minimally invasive surgery (MIS)	Pneumatic	Silicone rubber (Ecoflex 0030, Smooth-on)	No	–	Bending radius of novel fabricated soft flexible robotic manipulator follows an inverse curve with increasing air pressure	Design improvements and the establishment of a reliable model of the manipulator to predict its behavior	Sun (2016)	[73]
Robotic glove for rehabilitation	Robotic for chronic stroke survivors with Hemiparesis	Hydraulic soft actuators	Silicon (Elastosil M4601, Wacker Chemie AG, Germany)	Sliding mode controller (SMC) Bending and one for rotation	Three for each finger and two for thumb	Mathematical switches fulfill specific finger motion patterns	Improving robustness reinforced actuators	Polygerinos (2015)	[35]
Micro robotic tentacles with spiral bending capacity	Cardiovascular	Pneumatic	PDMS	Micro tube model using Euler–Bernoulli beam theory	–	Amplification of the micro tube	Modelling aspect for goal directed behavior and control	Paek (2015)	[74]

(*Continued*)

Table 2
(Continued)

Short Summary	Biomedical Applications	Type of Actuation	Fabrication Material	Mathematical Modelling	DOF	Striking Results	Challenges to Overcome	Lead Author (Year of Publication)	Reference
Sensing suit for developmentally delayed infants	A soft spandex for kicking enhancement	Motor-driven solutions	Thin channels of fabric	No	–	Angular sensors	Integration of the sensing suit with actuator suit and further human subject trials	Rogers (2015)	[75]
Soft robotic cardiac compression device	Direct cardiac compression (DCC) therapy for lymphedema, or as implantable artificial urethral sphincters used for end stage heart failure patients	Pneumatic	Polymer	No	–	Silicone laminate sleeve	Clinical trials and *in vivo* testing with the DCC device	Roche (2014)	[76]
Wearable electroencephalographic device	Emotion monitoring	Flexible electrode	Wearable EEG device	No	–	Distinguish through power spectrum analysis	To distinguish medium anxiety cases with greater sample size and diversified differences between gaming and clinical anxiety	Shruthi (2015)	[77]
Soft spatial fluidic elastomer manipulator	Design, kinematics and control to be interfaced into any soft fluidic medical devices	Pressurized fluid channels	Low durometer silicone rubbers	Multi-segment kinematic model	Eight and many passive DOFs	New spatial modular manipulator morphology design to suit for automation	Actuator design to consider the rupturing or failure of the elastic material, optimal plastic deformation or dynamic material fatigue	Marchese (2015)	[78]
Soft Oral rehabilitation robot (SORR)	Mandibular mobility disorders	Pneumatic	Silicone rubber (Ecoflex 0030, Smooth-on)	Static modelling	Three	Silicone-based SPA is viable to open the mouth more than 40 mm elongation and around 20N force output	Advanced self-conscious robot control by patients using surface EMG (sEMG) signal of the facial muscles development of a compact actuation and control system, clinical trials on real patients	Sun (2015)	[79]
Poroelastic foams fabrication of soft robots	Extension/ flexion	FEAs	PDMS	Kozeny–Carman (KC) model	–	Foams as a new material	Porous network limitation, tear down during overinflation	Murray (2015)	[80]

Table 2
(Continued)

Short Summary	Biomedical Applications	Type of Actuation	Fabrication Material	Mathematical Modelling	DOF	Striking Results	Challenges to Overcome	Lead Author (Year of Publication)	Reference
Fluidic elastomer snake	Rescue and surgical applications	Pneumatic	Silicone rubber (Smooth-on Ecoflex 0030)	No	–	Achieved high curvature values	Optimized robot mechanical design and dynamic modelling to accurately simulate and improved performance	Luo (2014)	[81]
Soft robotic fish	High body complaint soft robots	FEAs	Silicone rubber (Mold Star 15; Smooth-on, Easton, PA)	Static model	–	Self-contained continuum-body motion	Model valid for small deformation, external forces not considered	Marchese (2014)	[82]
Thermally tunable composites for soft robots	Novel material for fabrication of soft robots	No	Self-healing wax-coated composites	Minimal canonical model	–	Thermally tunable composites exhibit large change in volume, robust self-healing	Optimal heating parameters with minimum rupture, dissipation and plastic deformations	Cheng (2014)	[83]
Wearable tactile keypad	Streachable electronics for wearable sensing	Hydraulic soft actuators	PDMS	No	–	Device sensitivity	–	Kramer (2011)	[32]
Jamming technology for soft robotics	Negative air for jamming materials	Pneumatic	Silicone rubber	No	Eight	Universal handling	Soft, energy efficient vacuum pump	Steltz (2010)	[84]

5. Conclusion

It is evident by now that soft robots bring a new way to look into robotics for future generations, which will attract investors and companies for product commercialization. It is also to be noted here that soft robotics offer the potential not to compete with conventional robotics, but to tackle a set of problems that existing technologies have not been able to solve. The vast biomedical applications of soft robotics in rehabilitation, tissue engineering, soft biological cell biology, flexible surgical manipulators, *etc.* are overwhelming and call for a serious investment in research focused on the fabrication and material synthesis of flexible, dexterous, and cost-effective cross-linked polymers. There are abundant examples of soft robotics revolutionizing areas beyond biomedical research, such as disaster management, rescue operations, and field exploration. The question that stands now is whether innovations in rapid prototyping techniques such as soft lithography and 3D printing will allow manufacturers to print an entire robot that will be inexpensive, easy to use, and satisfy market demand. We can only be optimistic and work together to make this new technology grow faster and bring out a sustained environment in which human–robot interaction can rise to a new level.

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References

[1] M. Carmel, Soft robotics: A perspective—Current trends and prospects for the future, *Soft Robotics*, *1*(1), 2014, 5–11.

[2] K. Sangbae, C. Laschi, and B. Trimmer, Soft robotics: A bioinspired evolution in robotics, *Trends in Biotechnology*, *31*(5), 2013, 287–294.

[3] K. Autumn, C. Majidi, R.E. Groff, A. Dittmore, and R. Fearing, Effective elastic modulus of isolated gecko setal arrays, *Journal of Experimental Biology*, *209*(18), 2006, 3558–3568.

[4] D. Trivedi, C.D. Rahn, W.M. Kier, and I.D. Walker, Soft robotics: Biological inspiration, state of the art, and future research, *Applied Bionics and Biomechanics*, *5*, 2008, 99–117.

[5] R. Deimel and O. Brock, A novel type of compliant, underactuated robotic hand for dexterous grasping, *The International Journal of Robotics Research*, *35*(1–3), 2016, 0278364915592961.

[6] M.T. Tolley, R.F. Shepherd, B. Mosadegh, K.C. Galloway, M. Wehner, M. Karpelson, R.J. Wood, and G.M. Whitesides, A resilient, untethered soft robot, *Soft Robotics*, *1*, 2014, 213–223.

[7] R.J. Full, *Comprehensive Physiology* (Wiley, 1997), 853–930.

[8] R. Daniela and M.T. Tolley, Design, fabrication and control of soft robots, *Nature*, *521*(7553), 2015, 467–475.

[9] M.H. Dickinson, C.T. Farley, R.J, Full, M.A. Koehl, R. Kram, and S. Lehmanet, How animals move: An integrative view, *Science*, *288*(5483), 2000, 100–106.

[10] S.L. Montgomery, Carnivorous caterpillars: The behavior, biogeography and conservation of Eupithecia (Lepidoptera: Geometridae) in the Hawaiian Islands, *GeoJournal*, *7*(6), 1983, 549–556.

[11] S. Seok, C.D. Onal, R. Wood, D. Rus, and S. Kim, Peristaltic locomotion with antagonistic actuators in soft robotics, *IEEE International Conf. on Robotics and Automation (ICRA)*, Anchorage, Alaska, 2010, 1228–1233.

[12] S. Sanan, P.S. Lynn, and S.T. Griffith, Pneumatic torsional actuators for inflatable robots, *Journal of Mechanisms and Robotics*, *6*(3), 2014, 031003.

[13] H.T. Lin, G.G. Leisk, and B. Trimmer, GoQBot: A caterpillar-inspired soft-bodied rolling robot, *Bioinspiration & Biomimetics*, *6*(2), 2011, 026007.

[14] S. Seok, C.D. Onal, K.J. Cho, R.J. Wood, D. Rus, and S. Kim, Meshworm: A peristaltic soft robot with antagonistic nickel titanium coil actuators, *Mechatronics, IEEE/ASME Transactions*, *18*(5), 2013, 1485–1497.

[15] T. Barry, A journal of soft robotics: Why now? *Soft Robotics*, *1*(1), 2014, 1–4.

[16] V. Vitiello, S.L. Lee, T.P. Cundy, and G.Z. Yang, Emerging robotic platforms for minimally invasive surgery, *Biomedical Engineering, IEEE Reviews*, *6*, 2013, 111–126.

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

[18] A. Loeve, B. Paul, and D. Jenny, Scopes too flexible... and too stiff, *IEEE Pulse*, *1*(3), 2010, 26–41.

[19] Development of a multi-module STIFF-FLOP manipulator, Available at http://www.stiff-flop.eu (accessed June 9, 2016).

[20] R. Tommaso, M. Cianchetti, G. Gerboni, I.D. Falco, and A. Menciassi, A soft modular manipulator for minimally invasive surgery: Design and characterization of a single module, *IEEE Transactions on Robotics*, *32*(1), 2016, 187–200.

[21] P. Dupont, A. Gosline, N. Vasilyev, J. Lock, E. Butler, C. Folk, A. Cohen, R. Chen, G. Schmitz, H. Ren, and P. del Nido, Concentric tube robots for minimally invasive surgery, *Hamlyn Symposium on Medical Robotics*, London, UK, 2012, 7, 8.

[22] G. Joshua, Y. Ding, A. Harris, T. McKenna, P. Polygerinos, D. Holland, A. Moser, and C. Walsh, Shape deposition manufacturing of a soft, atraumatic, deployable surgical grasper, *Journal of Medical Devices*, *8*(3), 2014, 030927.

[23] K. Yeongjin, S.S. Cheng, and J.P. Desai, Towards the development of a spring-based continuum robot for neurosurgery, *Proc. in SPIE Medical Imaging*, Renaissance Orlando, Florida, 21–26 February 2015, 94151Q–94151Q.

[24] L. Xinquan, C. Lee, and H. Ren, Towards a micro pneumatic actuator with large bending deformation for medical interventions, *Proc. in 7th WACBE World Congress on Bioengineering*, Singapore, 2015, 76–79.

[25] W.H. Chang and Y.H. Kim, Robot-assisted therapy in stroke rehabilitation, *Journal of Stroke*, *15*(3), 2013, 174–181.

[26] C. Majidi, Soft robotics: A perspective—Current trends and prospects for the future, *Soft Robotics*, *1*(1), 2014, 5–11.

[27] J.A. Blaya and H. Herr, Adaptive control of a variable-impedance ankle-foot orthosis to assist drop-foot gait, *IEEE Transactions on Neural Systems Rehabilitation Engineering*, *12*(1), 2004, 24–31.

[28] E.C. Goldfield, Y.L. Park, B.R. Chen, W.H. Hsu, D. Young, M. Wehner, D. Newman, and R. Nagpal, Bio-inspired design of soft robotic assistive devices: The interface of physics, biology, and behavior, *Ecological Psychology*, *24*(4), 2012, 300–327.

[29] D. Marculescu, R. Marculescu, N.H. Zamora, P. Stanley-Marbell, P.K. Khosla, S. Park, S. Jayaraman, S. Jung, C. Lauterbach, W. Weber, T. Kirstein, D. Cottet, J. Grzyb, G. Troster, M. Jones, T. Martin, and Z. Nakad, Electronic textiles: A platform for pervasive computing, *Proceedings of the IEEE*, *91*(12), 2003, 1995–2018.

[30] D. Kim, Y. Kim, J. Wu, Z. Liu, J. Song, H. Kim, Y. Huang, K. Hwang, and J. Rogers, Ultrathin silicon circuits with strain-isolation layers and mesh layouts for high-performance electronics on fabric, vinyl, leather, and paper, *Advanced Materials*, *21*(36), 2009, 3703–3707.

[31] J.A. Rogers and Y. Huang, A curvy, stretchy future for electronics, *Proceedings of the National Academy of Sciences of the United States of America*, *106*(27), 2009, 10875–10876.

[32] R.K. Kramer, M. Carmel, and J.W. Robert, Wearable tactile keypad with stretchable artificial skin, *IEEE International Conf. on Robotics and Automation*, Shanghai, China, 2011, 1103–1107.

[33] Y.L. Park, B.R. Chen, D. Young, L. Stirling, R.J. Wood, E.C. Goldfield, and R. Nagpal, Design and control of a bio-inspired soft wearable robotic device for ankle-foot rehabilitation, *Bioinspiration & Biomimetics*, *9*(1), 2014, 016007.

[34] Y. Mengüç, Y.L. Park, H. Pei, D. Vogt, P.M. Aubin, E. Winchell, L. Fluke, L. Stirling, R.J. Wood, and C.J. Walsh, Wearable soft sensing suit for human gait measurement, *The International Journal of Robotics Research*, *33*(14), 2014, 0278364914543793.

[35] P. Polygerinos, Z. Wang, K.C. Galloway, R.J. Wood, and C.J. Walsh, Soft robotic glove for combined assistance and at-home rehabilitation, *Robotics and Autonomous Systems*, *73*, 2015, 135–143.

[36] T. Barry, H.T. Lin, A. Baryshyan, G. Leisk, and D.L. Kaplan, Towards a biomorphic soft robot: design constraints and solutions, *4th IEEE RAS & EMBS Biomedical Robotics and Biomechatronics (BioRob)*, Rome, Italy, 2012, 599–605.

[37] D. Hur, B.D. Matthews, A. Mammoto, M. Montoya-Zavala, and H.Y. Hsin, Reconstituting organ-level lung functions on a chip, *Science*, *328*(5986), 2010, 1662–1668.

[38] J.C. Nawroth, H. Lee, A.W. Feinberg, C.M. Rippinger, M.L. McCain, A. Grosberg, J.O. Dabiri, and K.K. Parker, A tissue-engineered jellyfish with biomimetic propulsion, *Nature Biotechnology*, *30*(8), 2012, 792–797.

[39] D.H. Kim, J. Viventi, J.J. Amsden, J. Xiao, L. Vigeland, Y.S. Kim, J.A. Panilaitis, E.S. Frechette, D. Contreras, and D.L. Kaplan, Dissolvable films of silk fibroin for ultrathin conformal bio-integrated electronics, *Nature Materials*, *9*(6), 511–517.

[40] K. Numata and D.L. Kaplan, Silk-based delivery systems of bioactive molecules, *Advanced Drug Delivery Reviews*, *62*(15), 2010, 1497–1508.

[41] S. Bhumiratana, W.L. Grayson, A. Castaneda, D.N. Rockwood, E.S. Gil, D.L. Kaplan, and G. Vunjak-Novakovic, Nucleation and growth of mineralized bone matrix on silk-hydroxyapatite composite scaffolds, *Biomaterials*, *32*(11), 2011, 2812–2820.

[42] V. Chan, K. Park, M.B. Collens, H. Kong, T.A. Saif, and R. Bashir, Development of miniaturized walking biological machines, *Scientific Reports*, *2*, 2012, 857: 1–8.

[43] X. Liang, Y. Sun, and H. Ren, A flexible fabrication approach toward the shape engineering of microscale soft pneumatic actuators, *IEEE Robotics and Automation Letters*, *2*(1), 2017, 165–170.

[44] H. Banerjee, Frequency dependent shape transitions in micro-confined biological cells, *International Journal of Advanced Information Science and Technology (IJAIST)*, *5*(4), 2016, 64–71.
[45] S.A. Morin, R.F. Shepherd, S.W. Kwok, A.A. Strokes, A. Nemiroski, and G.M. Whitesides, Camouflage and display for soft machines, *Science*, *337*(6096), 2012, 828–832.
[46] R.F. Shepherd, F. Illievski, W. Chi, S.A. Morin, A.A. Strokes, A.D. Mazzeo, X. Chen, M. Wang, and G.M. Whitesides, Multigait soft robot, *Proceedings of the National Academy of Sciences*, *108*(51), 2011, 20400–20403.
[47] F. Ilievski, A.D. Mazzeo, R.F. Shepherd, X. Chen, and G.M. Whitesides, Soft robotics for chemists, *Angewandte Chemie*, *50*(8), 2011, 1890–1895.
[48] R.V. Martinez, J.L. Branch, C.R. Fish, L. Jin, R.F. Shepherd, R. Nunes, Z. Suo, and G.M. Whitesides, Robotic tentacles with three-dimensional mobility based on flexible elastomers, *Advanced Materials*, *25*(2), 2013, 205–212.
[49] K.J. Cho, J.S. Koh, S. Kim, W.S. Chu, Y. Hong, and S.H. Ahn, Review of manufacturing processes for soft biomimetic robots, *International Journal of Precision Engineering and Manufacturing*, *10*(3), 2009, 171–181.
[50] L. Hod and M. Kurman, *Fabricated: The new world of 3D printing* (John Wiley & Sons, 2013).
[51] J.G. Cham, S.A. Bailey, J.E. Clark, R.J. Full, and M.R. Cutkosky, Fast and robust: Hexapedal robots via shape deposition manufacturing, *International Journal of Robotics Research*, *21*(10–11), 2002, 869–882.
[52] Y. Xia and G.M. Whitesides, Soft lithography, *Annual Review of Materials Science*, *28*(1), 1998, 153–184.
[53] S.P. Lacour, S. Wagner, Z. Huang, and Z. Suo, Stretchable gold conductors on elastomeric substrates, *Applied Physics Letter*, *82*(15), 2003, 2404–2406.
[54] J.A. Rogers, T. Someya, and Y. Huang, Materials and mechanics for stretchable electronics, *Science*, *327*(5973), 2010, 1603–1607.
[55] S. Cheng, Z. Wu, Microfluidic electronics, *Lab on a Chip*, *12*(16), 2012, 2782–2791.
[56] M.R. Cutkosky and S. Kim, Design and fabrication of multi-material structures for bioinspired robots, *Philosophical Transactions of the Royal Society*, *367*(1894), 2009, 1799–1813.
[57] E. Malone, M. Berry, and H. Lipson, Freeform fabrication and characterization of Zn-air batteries, *Rapid Prototyping Journal*, *14*(3), 2008, 128–140.
[58] R.J. Wood, The first biologically inspired at-scale robotic insect, *IEEE Transactions on Robotics*, *24*(2), 2008, 341–347.
[59] M. Cianchetti, V. Mattoli, B. Mazzolai, C. Laschi, and P. Dario, A new design methodology of electrostrictive actuators for bioinspired robotics, *Sensors and Actuators B: Chemical*, *142*(1), 2009, 288–297.
[60] C. Laschi, B. Mazzolai, V. Mattoli, M. Cianchetti, and P. Dario, Design of a biomimetic robotic octopus arm, *Bioinspiration & Biomimetics*, *4*(1), 2009, 015006.
[61] S. Kim, E. Hawkes, K. Cho, M. Jolda, J. Foley, and R. Wood, Micro artificial muscle fiber using NiTi spring for soft robotics, *Intelligent Robots and Systems, IROS, IEEE/RSJ International Conf.*, October 11–15, 2009, St. Louis, USA, 2009, 2228–2234.
[62] E.T. Roche, R. Wohlfarth, J.T. Overvelde, N.V. Vasilyev, F.A. Pigula, D.J. Mooney, K. Bertoldi, and C.J. Walsh, A bioinspired soft actuated material, *Advanced Materials*, *26*(8), 2014, 1200–1206.
[63] F. Daerden and L. Dirk, The concept and design of pleated pneumatic artificial muscles, *International Journal of Fluid Power*, *2*(3), 2001, 41–50.
[64] K. Suzumori, I. Shoichi, and T. Hiroshisa, Applying a flexible microactuator to robotic mechanisms, *Control Systems*, *IEEE*, *12*(1), 1992, 21–27.
[65] L. Hod, Challenges and opportunities for design, simulation, and fabrication of soft robots, *Soft Robotics*, *1*(1), 2014, 21–27.
[66] I. Fumiya and C. Laschi, Soft robotics: Challenges and perspectives, *Procedia Computer Science*, *7*, 2011, 99–102.
[67] R.J. Webster and B.A. Jones, Design and kinematic modeling of constant curvature continuum robots: A review, *The International Journal of Robotics Research*, *29*, 2010, 1661–1683.
[68] I.A. Gravagne, C.D. Rahn, and I.D. Walker, Large deflection dynamics and control for planar continuum robots, *IEEE/ASME Transactions on Mechatronics*, *8*(2), 2003, 299–307.
[69] R. Federico, M. Giorelli, M. Calisti, M. Cianchetti, and C. Laschi, Dynamic model of a multibending soft robot arm driven by cables, *IEEE Transactions on Robotics*, *30*(5), 2014, 1109–1122.
[70] K.C. Galloway, K.P. Becker, B. Phillips, J. Kirby, S. Licht, D. Tchernov, R.J. Wood, and D.F. Gruber, Soft robotic grippers for biological sampling on deep reefs, *Soft Robotics*, *3*(1), 2016, 23–33.
[71] H. Ren, X. Gu, and K.L. Tan, Human-compliant body-attached soft robots towards automatic cooperative ultrasound imaging, *IEEE 20th International Conf. on Computer Supported Cooperative Work in Design (CSCWD)*, Nanchang, China, 2016, 653–658.
[72] J. Morrow, H.-S. Shin, J. Torrey, R. Larkins, S. Dang, C.P. Grafflin, Y.-L. Park, and D. Berenson, Improving soft pneumatic actuator fingers through integration of soft sensors, position and force control, and rigid fingernails, *IEEE International Conference on Robotics and Automation (ICRA)*, Stockholm, Sweden, 2016, 5024–5031.
[73] S. Yi, S. Song, X. Liang, and H. Ren, A miniature soft robotic manipulator based on novel fabrication methods, *IEEE Robotics and Automation Letters*, *1*(2), 2016, 617–623.
[74] J. Paek, I. Cho, and J. Kim. Microrobotic tentacles with spiral bending capability based on shape-engineered elastomeric microtubes, *Scientific Reports 5*, 2015, 10768.
[75] E. Rogers, P. Polygerinos, C. Walsh, and E. Goldfield, Smart and connected actuated mobile and sensing suit to encourage motion in developmentally delayed infants, *Journal of Medical Devices*, *9*(3), 2015, 030914.
[76] R.T. Ellen, M.A. Horvath, A. Alazmani, K.C. Galloway, N.V. Vasilyev, D.J. Mooney, F.A. Pigula, and C.J.Walsh, Design and fabrication of a soft robotic direct cardiac compression device, *ASME 2015 International Design Engineering Technical Conf. and Computers and Information in Engineering Conf.*, Massachusetts, USA, 2015, V05AT08A042-052.
[77] S. Shruthi, Y. Liu, and R.C.H. Yeow, Development of a wearable electroencephalographic device for anxiety monitoring, *Journal of Medical Devices*, *9*(3), 2015, 030917.
[78] A.D. Marchese and D. Rus, Design, kinematics, and control of a soft spatial fluidic elastomer manipulator, *The International Journal of Robotics Research*, *35*(7), 2016, 0278364915587925.
[79] S. Yi, C.M. Lim, H.H. Tan, and H. Ren, Soft oral interventional rehabilitation robot based on low-profile soft pneumatic actuator, *IEEE International Conf. on Robotics and Automation (ICRA)*, Seattle, Washington, 2015, 2907–2912.
[80] B.C.M. Murray, X. An, S.S. Robinson, I.M. Meerbeek, K.W. O'Brien, H. Zhao, and R.F. Shepherd, Poroelastic foams for simple fabrication of complex soft robots, *Advanced Materials*, *27*(41), 2015, 6334–6340.
[81] L. Ming, W. Tao, F. Chen, T.K. Khuu, S. Ozel, and C.D. Onal, Design improvements and dynamic characterization on fluidic elastomer actuators for a soft robotic snake, *IEEE International Conf. on Technologies for Practical Robot Applications (TePRA)*, Woburn, Massachusetts, 2014, 1–6.
[82] A.D. Marchese, C.D. Onal, and D. Rus, Autonomous soft robotic fish capable of escape maneuvers using fluidic elastomer actuators, *Soft Robotics*, *1*(1), 2014, 75–87.
[83] N.G. Cheng, A. Gopinath, L. Wang, K. Iagnemma, and A.E. Hosoi, Thermally tunable, self-healing composites for soft robotic applications, *Macromolecular Materials and Engineering*, *299*(11), 2014, 1279–1284.
[84] E. Steltz, A. Mozeika, J. Rembisz, N. Corson, and H.M. Jaeger, Jamming as an enabling technology for soft robotics, *SPIE Smart Structures and Materials Nondestructive Evaluation and Health Monitoring*, San Diego, California, United States, 2010, 764225–764225.
[85] ABI Research, *Consumer and personal electronics* (New York: Allied Business Intelligence, Inc., 2013).
[86] Bank of America Merrill Lynch Research, *Thematic Investing, Robot Revolution-Global Robot & AI Primer, Equity*, 3rd November, 2015.
[87] T. Barry and G. Whitesides, An interview with George Whitesides, *Soft Robotics*, *1*(4), 2014, 233–235.

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