Review on Soft Grippers for Robotic Manipulators Performing Activities of Daily Living (ADLs)

Md. Tasnim Rana, Gabriella Davila Albor, Md Samiul Haque Sunny, , Kishor Lakshmi Narayanan, Mohammad H Rahman

Abstract

Keywords

1 Introduction (Dr. Kishor)

Context …. But …

Complication

Question

Hypothesis

ADLs: (Objects characteristics associated to the ADLs)

2 Materials

The choice of materials, specifically in soft robotics, is among the numerous critical aspects in defining the functionality, significance, and flexibility of a robotic system; in the development of soft grippers, this becomes much more critical. Here, an in-depth analysis will be presented concerning the various materials currently used in soft gripper construction, all having their special characteristics and abilities to fulfill certain specific application requirements of robotics. A most thorough analysis is presented here covering Ionic Polymer-Metal Composites, conducting polymers, carbon nanotubes, graphene, dielectric elastomers, shape memory polymers, biopolymers, gels, hydrogels, and haptic materials. All the unique responses of these materials to stimuli such as pH, temperature, electricity, light, and chemicals and their consequent applicability within different robotic contexts are examined in great depth. The intrinsic properties of this material, potential applications, and challenges are enlarged here, while dwelling on some limitations, including durability under adverse environments, and the way in which continuous research in this field should proceed to enhance functional longevity. A comparative analysis will, therefore, help in establishing appropriateness of the material chosen with respect to some operational demands, task objectives, and desired levels of sensitivity and adaptability, hence serving as a basis for knowledge in the optimal choice of materials in soft robot gripper design and development.

Add the ADLs comment for each material and look for 2 pictures for each material

2.1 Some important materials for soft grippers

Commented [GD1]: Materials used in soft grippers

The field of soft robotics is still evolving; current research desires to improve the ability, adaptability, and precision of the materials in use for soft grippers applied in different fields.

Gels and Hydrogels

Gels and hydrogels have been among the very important materials in the soft robotics field, with specific applications in adaptive, sensitive soft grippers under development. Their characteristics, such as high water content, being biologically acceptable, along with a soft equilibrium of mechanical properties simulating the living tissues, make them suitable for handling fragile objects in diverse fields, for example, medical methods, agriculture, or underwater inquiry. One of the great features of gels and hydrogels is p-H responsiveness. They can experience big changes in volume and mechanical properties due to changes in the environmental pH. This feature becomes even more useful in applications requiring precise and flexible responses toward changing local conditions, for instance, handling materials with a changeable pH without compromising structural integrity. (Material-1.pdf)[1] The other classic and important property granted upon gels and hydrogels concerns temperature responsiveness. On the occasion of temperature variation, these materials present a phase transition that can behave like a gripping force in soft robotics applications or be used to obtain controlled actuation.(Material-2.pdf)[2] Moreover, some gels and hydrogels are photo-responsive, which means they can change properties in response to light at specific wavelengths. This becomes useful in remote-controlled applications where light can be used to provide a non-contact catalyst that controls the action performed by the gripper itself—something indispensable in situations where non-invasiveness and precision are required (Material-3.pdf). [3]

Electrical responsiveness in gels and hydrogels opens avenues for their integration into devices requiring electrical conductivity or those where electrical stimuli can induce actuation. This property is most useful in controlled drug delivery systems and bio-applications where electrical signals are part of the functional requirement (More1.pdf).[4] The chemical responsiveness of gels and hydrogels increases their ability to be used in a variety of environments. They can answer to particular chemicals by means of swelling or de-swelling, which can come in very handy in changing chemical environments so that they may work adaptively and diversely(More2.pdf).[5]In the context of soft grippers, however, gels and hydrogels have some certain limitations. An important challenge for them is their relatively low mechanical strength with regard to stiffer materials, which might decrease their potential to carry loads. Moreover, it can also have a slower response time to stimuli, and this may affect the productivity of processes that involve fast actions. The fact that they require a controlled environment for the preservation of their properties, such as moisture levels, also brings challenges in their practical use(Material-1.pdf, Material-2.pdf).[1], [2]

Ionic Polymer-Metal Composites (IPMCs)

Among these, the IPMCs stand at the frontier of soft robotics and are more fitted for developing soft grippers. This material is also recognized for its low density, flexibility, and electric conductivity; it has become one of the favorites among researchers in the development of actuators and sensors in robotic systems. They have inherent properties of handling different objects delicately, imitating dexterity achieved by human fingers. These are exceptionally useful in environments where gentle interaction with fragile items is required. One very interesting property of the IPMCs is their responsiveness to changes in pH. Their shape or size can be changed based on the surrounding pH. This property is highly applicable in the cases of robotic systems operating in changing chemical environments, such as in chemical processing plants or laboratories in general that make use of a wide variety of chemical agents. The added advantage to their use in soft grippers within such an environment is the ability of IPMCs to respond to variations in pH. Material-1.pdf. [1]Temperature responsiveness contributes to the versatility of IPMCs. They can change their mechanical and electrical properties according to the changes in temperature, which is useful in surrounding conditions where the temperature keeps changing. This flexibility helps the soft grippers to perform at their optimal levels both when they are used under natural outdoor environments with climatic changes or indoor industrial applications involving heat conditions (Material-2.pdf).[2] A few IPMCs respond to photo-stimuli, that is, to light. This feature can be very useful in operations demanding a non-contact form of control or in environments where electromagnetic interference is a concern. Therefore, it allows the development of new control strategies for soft robotic applications using light-sensitive materials integrated within the IPMC structure (Material-3.pdf).[3] The electrical responsiveness of the IPMCs is perhaps their most defining feature. When subjected to an electric field, these materials bend or change shape, a property exploited widely in actuation applications. The ability to exactly control the movements made by the gripper is useful, for example, during tasks of high precision and delicacy such as microassembly or biomedical applications(More1.pdf).[4]IPMCs can be chemically tailored to respond to certain substances thus allowing them to be used with chemical sensitivity in specific environmental conditions. This property can be critical in such applications as chemical sorting or environmental monitoring, where the gripper needs to recognize and respond to very specific chemical stimuli (More2.pdf).[5] There are, however, limitations of IPMCs as well. The actuation forces are relatively lower compared to traditional actuators, which could become an important constraint in tasks where high force output is needed. Moreover, they are prone to humidity, and for their actuation, continuous power is required without fail—obstacles when being used at an inaccessible or nonpowered place. This paper outlines recent attempts towards improving stability, long-life, and reliability, material characteristics are reviewed to help speed up such advances, (Material-1.pdf, Material-2.pdf).[1], [2]Conductive polymers had been developing recently into revolutionizing the type of soft robotics under implementation into applications of making soft grippers. They present the remarkable ability to conduct electricity, combining properties that distinguish metals with the beneficial mechanical characteristics of polymers. Given the versatility of these types of material, they are ideal for a number of applications and purposes in creating flexible, adaptive gripping mechanisms. One exciting use of conducting polymers relies on its response to pH.. They can change their physical state in a drastic manner with changes in the pH of the surrounding environment. This property comes in very handy in scenarios when the gripper may come in contact with varying chemicals; thus, it can change its behavior or perform other special actions upon coming in contact with substances having varying levels of acidity or alkalinity. This versatility can be important in applications such as chemical laboratories or manufacturing industries handling a variety of chemical products (Material-1.pdf).[1] A second major characteristic of conducting polymers is temperature sensitivity. The conducting behavior of such materials may be modulated with changes in temperature, and such behavior may be exploited in applications for thermal sensing and actuation. This property allows for adaptive systems in soft grippers to adjust their grip force or stiffness in reaction to temperature change, thus maintaining safe and efficient handling of a given object without causing damage due to excessive force (Material-2.pdf).[2]

Conducting polymers

Some of the conducting polymers show photo-responsiveness, meaning they change their electrical or physical properties when exposed to specific wavelengths of light. This feature enables new possibilities for the control systems based on light signals and therefore allows non-invasive and remote control of soft grippers—especially in scenarios where direct contact or established control approaches might not be possible (Material-3.pdf).[3] The most relevant property of conducting polymers is their electroactivity, which enables them to produce electrical responses. These materials change size or shape when exposed to an electric field. Such properties are used for actuation. In soft grippers, the electroactive properties of the material can be used to provide controlled movements where situations demand careful handling or light manipulation. The ability to control the movements of the gripper with a high degree of precision by using electrical signals makes conducting polymers a very promising material for many applications, such as micro-assembly, health care, and other cases, where light interaction with the environment is needed (More1.pdf).[4] Moreover, conducting polymers can be designed to be chemically responsive so that they interact with or sense specific chemicals in their environment. This property is of great importance in applications where the identification and handling of certain materials are required, thus improving safety and operational efficiency in applications such as chemical sorting or the handling of dangerous chemicals (More2.pdf).[5]Nevertheless, some of the limitations of conducting polymers exist in that they normally perform optimally under very narrow, specified conditions and sometimes become degraded over time if subjected to rigorous environments. They also, at times, have to be protected against possible short circuits or electrical breakdowns, especially under damp conditions.These challenges lead to the continuous research of increasing their lifespan and operational stability(Material-1.pdf, Material-2.pdf).[1], [2]

Carbon nanotubes (CNTs) and graphene

Carbon nanotubes and graphene are highly recognized as some of the best materials for nanotechnology and material science-in particular, relating to soft robotics. These carbon-based materials stand very high in importance because of their superior strength, very good electrical conductivities, and good thermal properties that make them highly suitable for broad applications. In the context of soft grippers, CNTs and graphene provide high sensitivity and actuation capability, as required by light and precise manipulations in advanced robotics. Interestingly, CNTs and graphene show pH responsiveness-the alteration of their electrical properties according to changes in pH-makes them detectors of chemical changes in their environment. This property becomes particularly important when soft grippers have to handle hazardous substances or operate in conditions with changing chemical composition. The capability of sensing and responding to changes in pH therefore provides the means for ensuring safety and reliability of operations in dynamically changing chemical environments. (Material-1.pdf).**[1]** Another important property of the CNTs and graphene is their temperature responsiveness. While realizing thermal sensing, these materials show changes in electrical conductivity with temperature. In such a way, it can enable a soft gripper to monitor in real-time the temperature of an object for safe handling of those items that are susceptible to heat or cold. The responsiveness increases the adaptability of the gripper, which is meant to perform optimally under different thermal conditions. (Material-2.pdf).**[2]** Both CNT and graphene are photo responsive materials that can transduce light into electrical energy, which can be useful in soft robotics for light-driven actuation or energy harvesting. These capabilities can extend the use of soft grippers with CNT or graphene beyond conventional settings to those far from any power source or places where the energy supply is limited. (Material-3.pdf).**[3]** The electrical responsiveness of CNTs and graphene outlines their suitability for application in soft robotics. While their shape or conductivity may change upon electrical stimulations, these materials are perfect for the fabrication of flexible, responsive soft grippers. Such electro activity may provide ways of having fine control-for instance, in the handling of fragile objects or those needing operation in confined spaces. Increased electrical conductivity by CNTs and graphene, further makes signal transmission easy, hence fastening the responsiveness and control of the gripper. (More1.pdf). **[4]**Atomically, CNTs and graphene can be functionalized by various molecules, thereby increasing their reactivity with target substances. In this case, chemical sensitivity is very important when particular material detection and/or processing is required. As an example, a soft gripper can be used in some selective sorting tasks, environmental monitoring, or healthcare, where the presence of some kind of chemical signature needs to be identified. (More2.pdf).**[5]** However, it is difficult to combine CNTs and graphene into soft grippers due to the highly refined technology their synthesis and processing require; often, properties cannot be ensured uniformly over big areas. Moreover, these require state-of-the-art fabrication techniques while integrating them into soft matrices to maintain their properties. Health and safety concerns come up while handling nanomaterials, and those need to be kept in mind when designing and operating the grippers. (Material-1.pdf, Material-2.pdf).**[1], [2]**

Dielectric elastomers (DEs)

Dielectric elastomers are the most advantageous among appearing soft actuating materials and are making a considerable contribution to the development of soft robotics, mostly in adaptive gripper design. They, in turn, boast unique properties such as high energy density, big deformability, and sensitivity to all kinds of stimuli, making them especially apt for designing adaptable and efficient soft grippers. The inherent flexibility and adaptability of DEs echo the dynamic requirements of trendy automation and biomedical applications. One of the distinct features of DEs is the possibility of engineering their response characteristics under a change in pH. Such a change in the pH level could be essential in applications where the soft gripper is used under varying acidity or alkalinity levels. The inclusion of pH-responsive materials in the DE matrix allows soft grippers to change their actuation behavior or signal changes in their environment, which is important in applications in sensitive environments such as chemical processing plants or biological environments (Material-1.pdf).[1] Temperature responsiveness in DEs takes this an inch further. These responsive materials may change their mechanical and electrical properties with temperature variations, therefore making the soft grippers adjust with the changes in environmental temperature. This property will be especially helpful in applications that require precision in handling objects which may be sensitive to temperature changes, to guarantee the safety and efficiency of the operating performance of the grippers. (Material-2.pdf).[2] While DEs are not naturally photo-responsive materials, with the inclusion of photo-sensitive materials, they can be made to respond to light stimuli. This extends the range of their application in procedures where light can actuate or control something without contact. In such cases, light may also trigger some activities where there is either remote or hazardous access, hence enhancing the safety and adaptability of the robotics system. (Material-3.pdf).[3] The electrical responsiveness of dielectric elastomers is arguably their most distinctive feature. Upon exposure to an electric field, dielectric elastomers exhibit considerable deformation, which facilitates controlled actuation. That is the feature that makes them mostly used in soft grippers since this feature enables the precision of control necessary for handling fragile or complicated items. Further, the effectiveness and change in energy associated with electrical actuation in dielectric elastomers often outweigh the ones for other materials and are useful in situations regarding energy savings. (More1.pdf).[4] Chemically, the dielectric elastomers can be designed to provide interaction at a chemical level with given substances and find thereby their application in those environments that require the possibility of chemical detection or interaction. The embedding of selective receptors or crafting of molecular imprints may enable DE-based soft grippers to serve in tasks that require some specificity.(More2.pdf).[5] While promising, the features of DEs are not without challenges. Actuation usually involves high voltages, a safety concern. Most DEs could also easily be compromised, both physically and mechanically, by intense or long-prolonged electrical loads through either an electrical breakdown mechanism or materials failure. There are the considerations of longevity, environmental stability, and other robustness concerns with a DE as well, necessary for applications that real DEs offer.(Material-1.pdf, Material-2.pdf).[1], [2]

Shape Memory Polymers (SMPs)

Shape Memory Polymers (SMPs) are the most interesting types of smart materials in the field of soft robotics, particularly adaptive and responsive gripping mechanisms. SMPs can change shape from an original shape to a deformed shape with the application of an external stimulus, such as heat, light, or an electric field. This distinct characteristic gets innovative solutions for designing soft robotic systems simulating the flexibility and agility of the human hand in the performance of the Activities of Daily Living, or ADLs. SMPs with pH-responsiveness are those that can be synthesized to change either shape or mechanical properties in response to environmental pH changes. This feature is specifically valuable when the gripper may expose the object to various chemical environments, where it automatically changes its grip force or shape for safe and efficient handling of different objects in a chemically sensitive scenario. (Material-1.pdf).[1] The most striking feature of SMPs is the degree of temperature responsiveness; that is, they return to their original shape with some thermal threshold. This property will help to design self-adjusting soft grippers with respect to temperature changes that can be important in fluctuating thermal environments or in applications where handling objects of different temperatures without manual intervention is required. (Material-2.pdf).[2] While SMPs themselves are not naturally photo-responsive, they can be arranged with specific wavelengths of light for remote non-contact actuation of the soft grippers. Notably, this feature is useful where direct handling and environmental disturbance must be stopped for safe operation and to protect the integrity of the manipulated items. (Material-3.pdf).[3] Electrical responsiveness in SMPs is less common and can be obtained by incorporating conductive materials into the polymers so that they can respond to electrical stimuli. This functionality provides a means for accurate control of the gripping action, which is very relevant when performing tasks needing great accuracy and delicacy. The same functionality leads to energy efficiency because actuation can be achieved with low-power electrical signals. (More1.pdf).[4] Chemically, SMPs can be tailored to respond to specific substances or conditions, rendering them very useful in applications requiring chemical responsiveness. For example, SMP-based grippers may be used in sorting where the distinction based on chemical composition is important, or in environments where chemical reactivity may influence the functionality of the gripper. (More2.pdf).[5]SPMs have their limitations despite their versatility. The requirement of an external stimulus for actuation may turn out to become a logistical nightmare, especially in applications in remote or hazardous environments. Other factors that need to be overcome are related to the resistance of the material to fatigue, its response time, and the precise control of the external stimuli to avoid undesired changes of shape for better optimization in soft robotic grippers.(Material-1.pdf, Material-2.pdf).[1], [2]

Biopolymers

Biopolymers, naturally occurring or bio-inspired polymers, have been finding increasing interest in soft robotics, in particular in the field of soft grippers for activities of daily living. The materials are considered biocompatible, environmentally friendly, and often biodegradable, making them highly attractive when ecological sensitivity is an issue. Their intrinsic properties can be used or engineered to respond to various stimuli, thereby enabling the realization of adaptive and intelligent systems for complex tasks. The pH sensitivity of biopolymers offers the ability for the soft gripper to interact with its environment dynamically. That is very useful for applications where the operating robot is under conditions that are mostly changing in its chemistry, whereby responding to changes in pH, the gripper can change in mechanical properties or even in shape, therefore making sure of safety and dexterous manipulation without compromising structural integrity. Material-1.pdf.[1] Thermal-responsive biopolymers give additional functionality to soft grippers and allow their successful use under various temperature conditions. These materials can show elasticity, morphological changes, or any other physical changes with the variation of temperature, which can be used by the gripper to change the grip and apply force accordingly. This could be important in applications where manipulation might require objects sensitive to temperature or function within changing thermal profiles. (Material-2.pdf).[2] While not a natural inherent property, photo-responsiveness can be conferred on biopolymers, thus offering the potential for light-driven actuation and control. This property is of particular interest in applications where non-invasive activation is required and allows for remote control of the gripper operation-a key feature in sterile, hazardous, or inaccessible environments. (Material-3.pdf).[3] Conductive elements or compounds allow electrical responsiveness in biopolymers, which, with control, enables the fine-tuning of movements and the forces applied by the gripper. This means that the soft gripper has an active response to electrical stimuli, which allows it to handle such complex delicate operations as those performed in careful handling or sophisticated assembly applications. This attribute expands the use of soft robotic systems within industrial, medical, and exploratory fields..(More1.pdf).[4] Chemically responsive biopolymers can selectively interact with specific substances, which allows soft grippers to sense and act upon chemical cues in the environment. This feature is of utmost importance in a range of applications that involve automatic sorting mechanisms, gentle manipulation of chemical materials, or operations in chemically unstable environments where the gripper must recognize and adapt to chemical changes to function effectively.(More2.pdf).[5] While the benefits are very promising, the limitations of using biopolymers in soft grippers come down to susceptibility to environmental degradation, the potential for lower mechanical robustness of synthetic materials, and careful calibration is required to achieve consistent responses to stimuli. Further, the scalability and cost-effectiveness of biopolymer-based systems remain challenges to be addressed for widespread adoption. (Material-1.pdf, Material-2.pdf). [1], [2]

In the table, each of the materials has a different set of properties, and the choice between them is dependent on the requirements of the application, including the operating environment, type of assignment, sensitivity, and flexibility. Table 1 gives a general view of the relative properties of materials discussed above.

RANA : complete the table of e[1]xamples please

Table 1: Examples of use of the type of materials commonly used in soft grippers and their stimulating properties.

Type of Materials	pH-Responsive	Temperature Responsive	Photo Responsive	Electrical Responsive	Chemical Responsive	Special Properties
Gels and Hydrogels	Development of logic gates with sensing.[6]	Oil recovery using synthesized polyvinyl	Photo-responsive DNA supramolecular	self-sensing actuators using highly stretchable and	Yes	

Commented [GD6]: [#]
J. Meng *et al.*, *"Novel Environmentally Responsive Polyvinyl Polyamine Hydrogels Capable of Phase Transformation with Temperature for Applications in Reservoir Profile Control," Gels, vol. 9, no. 12, p. 950, Dec. 2023, doi: https://doi.org/10.3390/gels9120950.*

Commented [GD2]: https://www.mdpi.com/2073-4360/11/10/1564

Commented [Ma3R2]:

	Surgical and therapeutic medical devices.[7] 4D printed, time-dependent, shape-changeable, stimuli-responsive soft robots that are currently controlled by heat, pH, and light stimulus.[8]	polyamine hydrogels.[9] Soft actuators in soft robotics using synthesized monolithic non-porous hydrogels.[10]	hydrogels, used as UV Radiometers could be applied in soft grippers for UV-sensitive operations.[11] “Thermo- and Photo-responsive Composite Hydrogels with Programmed Deformations” suitable for designing adaptive and responsive soft grippers.[12]	electrically conductive hydrogels with fast stimuli-responsive actuating performance. Other studies currently made can be adapted to be electrically responsive like the 4D responsive soft robot.		
IPMCs	Yes					
Conducting Polymers		Yes				
CNTs and Graphene			Yes			
Dielectric Elastomers				Yes		
Shape Memory Polymers						
Biopolymers	Yes					
Haptic material						

2.2 Materials Selection Criteria

Soft grippers use different stimuli, such as electricity, heat, light, chemicals, or pH, to change the shape and size of fingers and hands to grasp objects. Moreover, these materials also facilitate a wide range of object shapes and sizes, inherent safety, and delicate manipulation tasks. The following are some essential characteristics of soft robotic grippers, which need to be considered in selecting materials.

(a) ***Compliance:*** Compliance is a characteristic commonly observed in soft grippers, which are mainly fabricated using elastomeric substances like silicone, rubber, or other pliable polymers. This property enables these grippers to undergo deformation and adapt to the specific contours of the objects they are designed to grasp. The ability to accommodate objects of varied sizes and forms without requiring exact positioning is facilitated by this compliance.

(b) ***Safety:*** Safety is a key advantage of soft grippers since they include inherent characteristics that make them more suited for usage close to humans. This makes them a viable option for situations in which conventional rigid grippers could potentially provide a safety hazard.

(c) ***Versatility:*** The versatility of soft grippers enables them to effectively manipulate a diverse array of things, encompassing both delicate and asymmetrical items as well as those that are stiff

Commented [GD10]: https://pubs.rsc.org/en/content/articlelanding/2023/tc/d3tc00990d

Commented [GD4]: https://onlinelibrary.wiley.com/doi/pdfdirect/10.1002/aisy.202000186

Commented [GD8]: https://link.springer.com/article/10.1007/s40242-023-2329-5

Commented [GDA7]: [#]
B. Strachota *et al.*, *“Exceptionally Fast Temperature-Responsive, Mechanically Strong and Extensible Monolithic Non-Porous Hydrogels: Poly(N-isopropylacrylamide) Intercalated with Hydroxypropyl Methylcellulose,” Gels, vol. 9, no. 12, p. 926, Dec. 2023, doi: https://doi.org/10.3390/gels9120926.*

Commented [GD5]: https://www.jove.com/t/64870/four-dimensional-printing-stimuli-responsive-hydrogel-based-soft

Commented [GD9]: https://pubs.rsc.org/en/content/articlelanding/2019/tb/c8tb02896f and inflexible. These machines demonstrate adaptability across various sectors, including food processing, manufacturing, and supply chain management.

(d) Customizability: *Customizability is a key feature of soft robotic grippers, as it enables the design to be modified according to individual application requirements. This allows for the creation of gripper fingers or actuators in different shapes and sizes.*

(e) Actuation methods: *Actuation methods: Soft grippers can be actuated by a range of techniques, including pneumatic, hydraulic, and shape-memory alloys. These approaches enable the achievement of accurate control over gripping force and motion.*

(f) Suction and adhesion: *Soft grippers often employ mechanisms such as suction or stickiness to securely grasp objects, rendering them particularly effective for manipulating flat or smooth surfaces.*

(g) ***Tactile sensing:*** Tactile sensing is a feature observed in certain sophisticated soft grippers, wherein tactile sensors are integrated into their surfaces. This integration enables these grippers to offer feedback regarding the grip and also detect the condition of the object being gripped.

(h) ***Applications:*** Soft robotic grippers are utilized in a diverse range of industries, encompassing manufacturing, healthcare, agriculture, and space exploration. They are particularly valuable in situations where objects have variable shapes, sizes, and materials.

2.3 Challenges in selecting Soft Grippers materials

Some materials, such as CNTs and graphene, while possessing high strength and conductivity, lack the flexibility that soft grippers often require, potentially limiting their application scope (Material-2.pdf).[2]

Haptic materials, though innovative in providing tactile feedback, face challenges in integrating with other systems and require further research to enhance their responsiveness and versatility (Material-3.pdf).[3]

3 Design Aspects:

3.1 Single Degree of Freedom (1-DoF) Soft Gripper

Grippers with a single degree of freedom have some fixed tasks to do where it can only provide a single functionality objectifying a certain object by shape change. Where the activation power triggers the actuation mode whether the system will actuate or not and it will have its driving force from different kind of source like pneumatic, hydraulic, magnetic, or other. In common case, soft gripper with single chamber to inflate or close pointing a single actuator performs a single task typically has one main actuation point or mechanism that enables it to perform a specific type of motion [Reference].[13]

For example, a particular case study can be observed from the work of Sam Z [Reference][14], for single degree of freedom soft robotics which has a single chamber for withholding its pneumatic pressure and actuate at a defined arctic shape. While pneumatic pressure has been given to the actuation point chamber through compressor capable of generating the required torque. Then the volumetric change of the actuation point would affect the movement as a predefined shape

Commented [ra11]: Shintake J, Cacucciolo V, Floreano D, Shea H. Soft robotic grippers. Adv Mater. 2018;30. https://doi.org/10.1002/adma.201707035

Commented [ra12]: Samadikhoshkho Z, Zareinia K, Janabi-Sharifi F. A brief review on robotic grippers classifications. 2019 IEEE Can Conf Electr Comput Eng CCECE 2019;2019:10–13 position. The bi-Bellows actuator, as illustrated in the diagram Fig:, can achieve bending angles that surpass +180° when subjected to pressures lower than 1.25 atm. The beam deflection model is deemed reliable when applied to exterior hoops, but its adequacy is compromised when used for interior hoops due to the presence of recurring end conditions. The measurement of strain is a valuable technique used to estimate the degree of bending, which requires meticulous implementation using force sensors or sub-actuator resolution. The model demonstrates less non-linearity in comparison to real-world observations, thereby necessitating additional research to enhance its accuracy. [Reference][15]

The modification can be achieved through the implementation of several cylindrical apertures capable of containing and maintaining air pressure. The utilization of many apertures in an actuator can augment the degree of freedom. Consequently, such an actuator has the potential to possess either a singular degree of freedom or multiple degrees of freedom, contingent upon the number of chambers present to sustain pneumatic pressure [Reference][16]. A projectile's final output depends on the extent of imposed constraints on its movement.

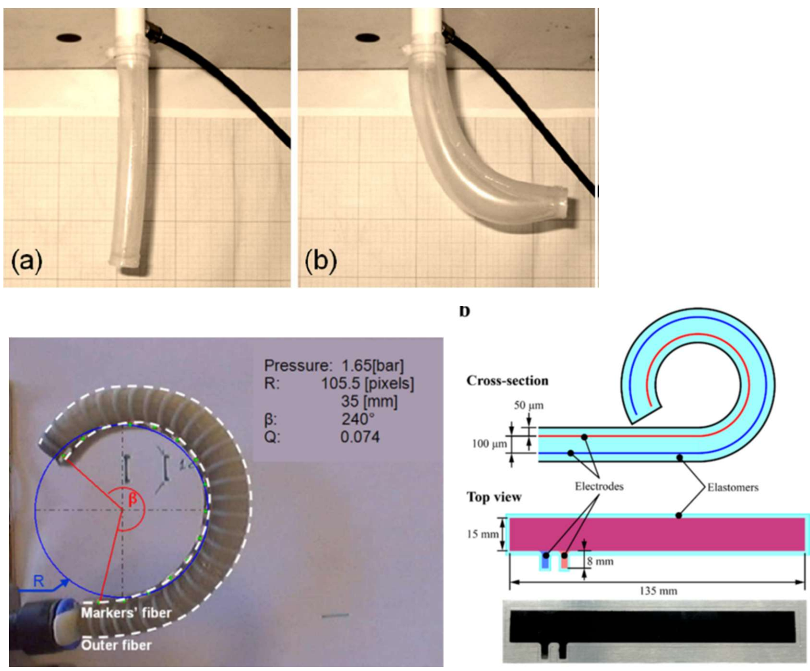


Fig: (a) Condition of a soft pneumatic actuator without applying partial pressure (b) Incase of applying partial pneumatic pressure [Reference][17] (c) The utilization of a pneumatic soft actuator incorporating a fiber Bragg grating (FBG) curvature sensor for the purpose of quantifying the deformation of such soft actuator.[Reference] [18] (d) The research paper introduces an ionic polymer-metal composite (IPMC) consisting of a block copolymer composed of polystyrene and poly(1-ethyl-3-methylimidazolium-4-styrenesulfonate), which serves as the active layer. The IPMC is immersed in an electrolyte solution containing an ionic liquid. [Reference] [19]

Commented [ra13]: Have to tag the below figure

Commented [ra14]: Nguyen AK, Russell A, Naclerio N, Vuong V, Huang H, Chui K,
Hawkes EW. A tri-stable soft robotic finger capable of pinch and
wrap grasps. Proc - IEEE Int Conf Robot Autom 2020;9028–9034
7. Kim Y, Cha Y. Soft pneumatic gripper with a tendon-driven soft
origami pump. Front Bioeng Biotechnol. 2020;8:1–11

Commented [ra15]: ParkW, Seo S, Bae J. A hybrid gripper with soft material and rigid
structures. IEEE Robot Autom Lett. 2019;4:65–72

Commented [ra16]: Shapiro, Y.; Wolf, A.; Gabor, K. Bi-bellows: Pneumatic Bending Actuator. Sens. Actuators A Phys. 2011, 167,
484–494.

Commented [ra17]: Skorina, E.H.; Luo, M.; Oo, W.Y.; Tao, W.; Chen, F.; Youssefian, S.; Rahbar, N.; Onal, C.D. Reverse Pneumatic
Artificial Muscles (RPAMs): Modeling, Integration, and Control. PLoS ONE 2018, 10.

Commented [ra18]: V. H. Nguyen, J. Kim, R. Tabassian, M. Kotal, K. Jun, J. H. Oh,
J. M. Son, M. T. Manzoor, K. J. Kim,I. K. Oh, Adv. Sci. 2019, 6, 1801196.

In above figure (D) A 1-degree of freedom soft gripper was equipped with an antagonistic actuator that utilized rolled dielectric elastomer actuators (DEAs). The actuator is composed of a central support structure, a flexible joint, and two coiled dielectric elastomer actuators (DEAs), enabling the gripper to move in both directions. The experimental results demonstrated that the system exhibited voltage-controlled angular displacement and torque capabilities of up to 2.2 degrees and 11.3 mN·mm, respectively, within the voltage range of 0-1200 V. The successful integration of rolled dielectric elastomer actuators (DEAs) into a soft gripper resulted in the effective grasping of items. This outcome underscores the potential of rolled DEAs in improving the performance of soft grippers with one degree of freedom (1-DoF) [Reference].[20]

Commented [ra19]: Zhao, H.; Li, Y.; Elsamadisi, A.; Shepherd, R. Scalable Manufacturing of High Force Wearable Soft Actuators.
Extreme Mech. Lett. 2015, 3, 89–104.

The two examples of single degree of freedom grippers possess the unique capability to perform tasks that are particular to a single shape. According to the depicted figure (C), it can be observed that the application of pneumatic pressure to the chamber results in a transformation of its shape from a straight position to a circular position. The findings indicate that the system can support objects of varying weights, up to its maximum strength capacity, to securely grasp objects with round surfaces. It has been observed that an increase in air pressure enables the gripper to effectively grasp objects of smaller diameter and larger weight [Reference].[21]

Commented [ra20]: Shintake, J.; Cacucciolo, V.; Floreano, D.; Shea, H. Soft Robotic Grippers. Adv. Mater. 2018, 30.

3.2 Dual Degree of Freedom(2-DoF) Soft Gripper :

In instances involving a dual degree of freedom, the soft gripper system is outfitted with a pair of actuation systems to enhance the flexibility of gripping objects and improve maneuverability. In certain instances, grippers employing pneumatic or hydraulic actuation may use a single actuation point with a separator wall. This phenomenon enables the soft gripper to exhibit two degrees of freedom (2-DoF) due to two distinct volumetric pressure differences.

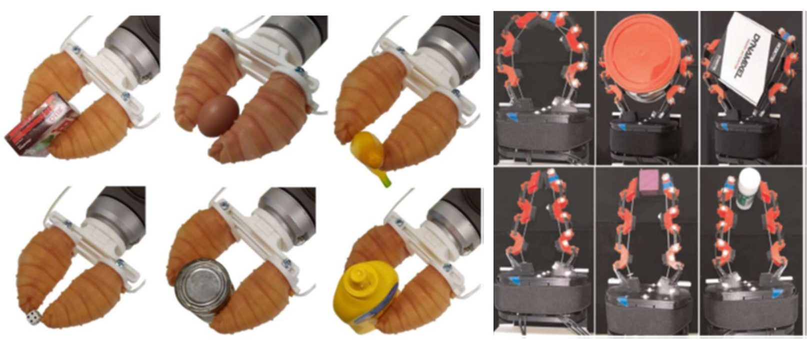


Fig:(a) Pneumatically Driven, Disposable, Soft Robotic Gripper Equipped with Retractable, Telescopic Fingers [Reference] [22] (b) The soft gripper employs power and pinch grip configurations to effectively grasp a wide range of items, shapes, and materials, while also adapting joint stiffness as necessary.[Reference] [23]

The incorporation of a haptic sensing system and data-driven kinematics into the PneuNets Actuator has introduced a new dimension to the field of soft gripper technology. This advancement holds the potential to enhance the flexibility of soft grippers.[Reference][24]

Commented [ra21]: L. Gerez and M. Liarokapis, "A Pneumatically Driven, Disposable, Soft Robotic Gripper Equipped with Retractable, Telescopic Fingers," 2020 8th IEEE RAS/EMBS International Conference for Biomedical Robotics and Biomechatronics (BioRob), New York, NY, USA, 2020, pp. 36-41, doi: 10.1109/BioRob49111.2020.9224292.

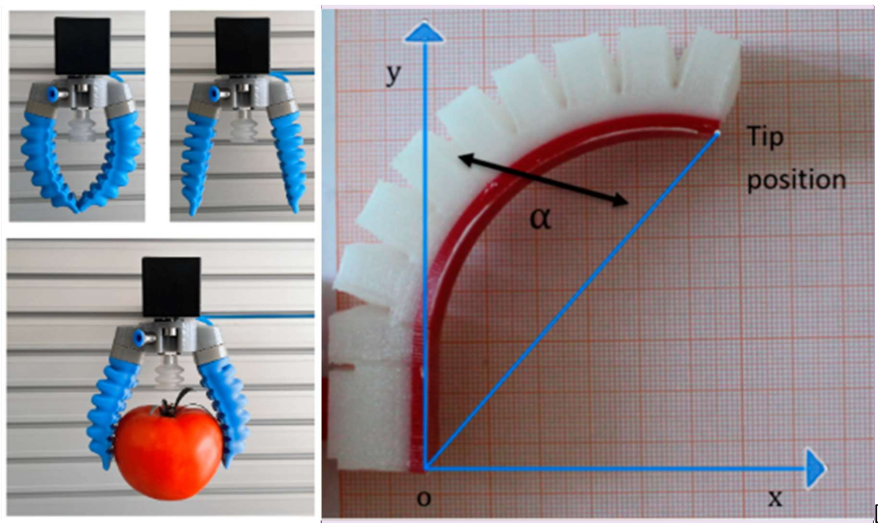
Commented [ra22]: I. Hussain, M. Malvezzi, D. Gan, and M. Z. Iqbal, "Compliant gripper design, prototyping, and modeling using screw theory formulation," *The International Journal of Robotics Research*, vol. 40, no. 1, pp. 0278364920947818, Aug. 2020.
DOI: 10.1177/0278364920947818

Commented [ra23]: M. Yu, X. Cheng, S. Peng, Y. Cao, Y. Lu, B. Li, X. Feng, Y. Zhang, H. Wang, Z. Jiao, P. Wang, and L. Zhao, "A self-sensing soft pneumatic actuator with closed-loop control for haptic feedback wearable devices," *Materials & Design*, vol. 223, p. 111149, Nov. 2022.
DOI: 10.1016/j.matdes.2022.111149

The PneuNets bending actuators, which serve as passive components in soft robotics, operate by utilising pneumatic pressure as a means of control. These actuators possess compliance and plasticity, allowing them to imitate natural biological movements. These materials can conform to complex surfaces in a gentle manner, making them appropriate for a wide range of applications such as object manipulation and medical treatments. Within soft robotics, incorporating passive actuators plays a pivotal role in advancing robotic systems by enhancing their dexterity and precision [Reference].[25]

Commented [ra24]: https://www.mdpi.com/2076-0825/11/2/58

Commented [ra25]: https://www.mdpi.com/2072-666X/11/5/485



[26]

Fig: (a)PeuNet in performance (b) Elastration of movement diagram with a bending angle α [Reference][27]

Commented [ra26]: X. Zhang, S. Yu, J. Dai, A. E. Oseyemi, L. Liu, N. Du, and F. Lv, "A Modular Soft Gripper with Combined Pneu-Net Actuators," *Actuators*, vol. 12, no. 4, p. 172, Apr. 2023.
DOI: 10.3390/act12040172

The provided diagram (B) illustrates a fundamental PneuNet gripper, characterized by an angle denoted as α. This angle's measurement is contingent on the system's pneumatic pressure. The structure, composed of a pliable material, exhibits an inherent capacity for expansion when subjected to pressure, functioning akin to an inflatable chamber. However, when imposing constraints on the mobility of one side while allowing freedom on the other side, the system will exhibit bending behavior towards the limited side, resulting in a gripping effect. As the applied pressure increases, a corresponding increase in the counterforce is observed while holding an object. One notable feature of this soft gripper is its ability to effectively withstand additional force applied to the contact surface where the object is grasped, while simultaneously supplying supplementary air pressure to the gripper.[Reference][28]

Commented [ra27]: Su, H.; Hou, X.; Zhang, X.; Qi, W.; Cai, S.; Xiong, X.; Guo, J. Pneumatic Soft Robots: Challenges and Benefits. *Actuators* **2022**, *11*, 92

3.3 Muli- Degrees of Freedom (3+ DoF) Soft Gripper

The term "multi-3DOF gripper" generally denotes a gripper that possesses several degrees of freedom (DOF) inside a three-dimensional spatial framework. This implies that the object can move and adapt its position in several manners across three axes, hence providing enhanced flexibility and dexterity for the purpose of grabbing and manipulating things inside three-dimensional settings. Different chamber forms of bendable actuators have been investigated for fields manipulation and rehabilitation. These actuators are inadequate for intricate manipulation jobs or unbuilt settings, though, as they can only bend in a two-dimensional plane. To modify the heading direction in three dimensions, multi-degree-of-freedom actuators featuring several actuation chambers have been created. One way to achieve hyper-redundant robot assembly, actuation, and fabrication is through the modularization of soft actuators. Nevertheless, there is currently no standard framework for multi-DoF actuator design, nor is there a quick fabrication technique for assembling a manipulator that has several actuators [Reference].[29]

Commented [ra28]:
IEEE Format:
B. Zhang, C. Hu, P. Yang, Z. Liao, and H. Liao, "Design and Modularization of Multi-DoF Soft Robotic Actuators," *IEEE Robotics and Automation Letters*, vol. 4, no. 3, pp. 2645-2652, Jul. 2019.

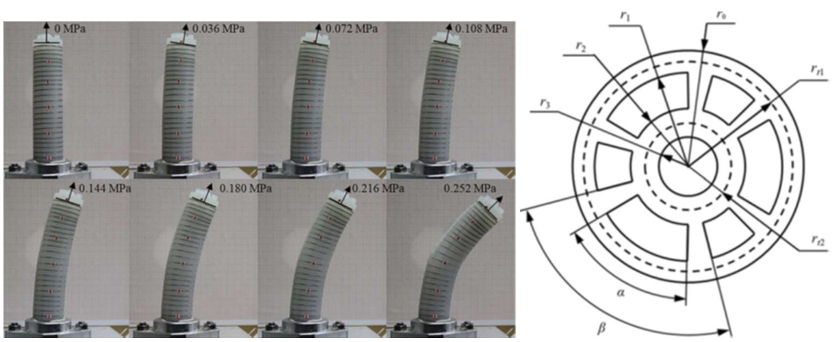


Fig: (a) movement of the actuator upon applied pressure through differential pressure blocks (b) Cross section of the actuator which shows the six different cavities to express the movement more than 3 DoF [Reference].[29]

Commented [ra29]:
IEEE Format:
B. Zhang, C. Hu, P. Yang, Z. Liao, and H. Liao, "Design and Modularization of Multi-DoF Soft Robotic Actuators," *IEEE Robotics and Automation Letters*, vol. 4, no. 3, pp. 2645-2652, Jul. 2019.

The main body of a soft robot is often constructed from a soft material with significant flexibility. Soft elastic material, robot size, and complex internal systems all put constraints on the manufacturing process. When nonlinear, soft materials are used in production, conventional production techniques no longer apply. Soft lithography and shape-deposition manufacturing are the main fabrication processes, and they work well for straightforward channel architectures. Casting with a retractable pin, lost-wax casting, and 3D printing are more options. Although these techniques can be used to complicated 3-D constructions, their properties and associated costs are limited [Reference].[30] The air compressor was selected as the primary source of pneumatic power. The acquisition of pressured air for experimental purposes was accomplished by the utilization of an oil mist separator and a pressure regulating valve. The chambers of the soft actuator resembling a trunk were inflated with compressed air using electrical proportional valves [Reference]. The electrical proportional valve can adjust its output air pressure based on the voltage signal received from the electronic control circuit. The electrical proportional valve under consideration is the SMC ITV0050-3BS. It is designed to operate within a specified input control signal range of 0 V to 5 V. The valve's output pressure can vary between 0.001 MPa and 0.9 MPa. It is worth noting that the valve exhibits a linearity of ±1% in its pressure output [Reference].[31]

Commented [ra30]: M.Wehner et al., “An integrated design and fabrication strategy for entirely soft, autonomous robots,” Nature, vol. 536, no. 7617, pp. 451–455, Aug. 2016. [Online]. Available: https://www.nature.com/articles/nature19100

Commented [ra31]: C. Lee, M. Kim, Y. J. Kim, N. Hong, S. Ryu, H. J. Kim, and S. Kim,
“Soft robot review,” International Journal of Control, Automation and
Systems, vol. 15, no. 1, pp. 3–15, 2017.

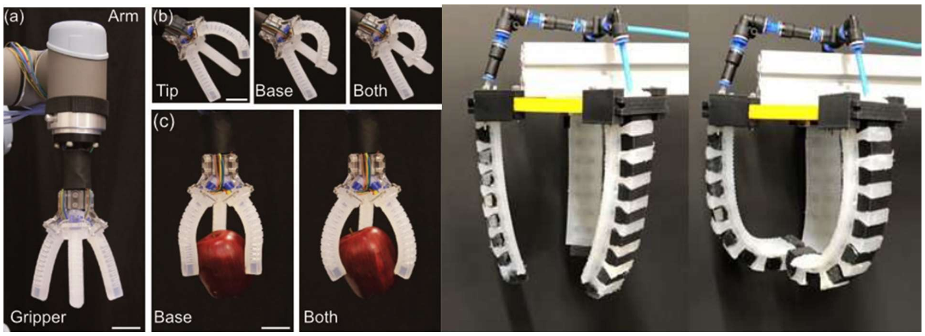
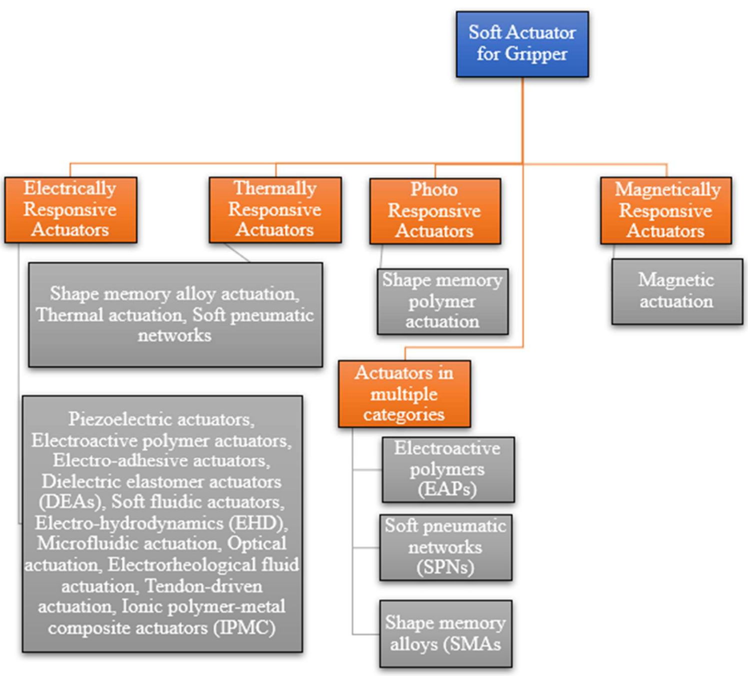


Fig: The fingers of these 3 DoF grippers are actuated by a Festo pneumatic valve manifold, with inflation in 10 kPa increments up to a maximum of 200 kPa.

There are other works where hybrid type gripper has been used for more than 3 DoF grippers. The fingers are actuated using a Festo pneumatic valve manifold, inflating in 10 kPa steps, with a maximum pressure of 200 kPa. A 3D printed mount attaches the gripper to a UR5 robot arm, and MATLAB controls the inflation [Reference].[32] An autonomous grasping algorithm employs soft contact sensors in each finger to ensure secure object contact before attempting to lift, enhancing grasping reliability.

Commented [ra32]: W. Park, S. Seo, and J. Bae, "A Hybrid Gripper with Soft Material and Rigid Structures," *IEEE Robotics and Automation Letters*, vol. 4, no. 1, pp. 65-70, Jan. 2019.



4 Soft Actuation Technology

Table: Type of soft actuator for soft gripper

Type of Actuation	Advantages	Limitations	Force Output	Materials Used	Cost	Ref.
Pneumatic Actuation[33]	High dexterity, adaptable, safe, customizable	Limited payload, requires an air source	Medium to High	Flexible materials, elastomers	Moderate	
Vacuum Actuation[34]	Efficient, low cost, lightweight, non-contact	Limited range of motion	Low to Medium	Flexible materials, suction cups	Low	
Cable-Driven Actuation[35]	Precise control, versatile, high force output	Complex design, limited speed	High	Cables, materials	Moderate	
Shape Memory Alloy Actuation[36]	Compact, high force output, shape-changing properties	Slow response, limited cycle life	High	Shape-memory alloys	High	
Electroactive Polymer Actuation[37]	Soft, lightweight, flexible, low power consumption	Low force output, slow response	Low to Medium	Electroactive polymers	Moderate	
Electro-adhesive Actuation[38]	High grip strength, low energy consumption	Limited range, may damage surfaces	Medium to High	Electro-adhesive materials	Low to Moderate	
Hydraulic Actuation[39]	High force, durable, suitable for heavy loads	Complex infrastructure, heavy	High	Hydraulic fluids, rigid parts	High	
Thermal Actuation[40]	Simple, lightweight, low power, suitable for delicate objects	Limited force, slow response	Low to Medium	Shape-memory alloys, polymers	Low to Moderate	
Pneumatic Artificial Muscles (PAMs)[41]	High force-to-weight ratio, adaptable	Require pressurized air source	High	Rubber-like materials, textiles	Moderate	
Dielectric Elastomer Actuators (DEAs)	Lightweight, soft, high strain, low power consumption	Limited force, wear and tear	Low to Medium	Elastomers, compliant materials	Moderate	
Soft Fluidic Actuators[33]	Versatile, adaptable, low cost	Limited force, complex control	Low to Medium	Flexible materials, elastomers	Low to Moderate	
Ferrofluid-Based Actuation[42]	Flexible, shape-changing, low power consumption	Limited force, requires ferrofluid	Low to Medium	Ferrofluids, magnetic fields	Low to Moderate	
Soft Pneumatic Networks[43]	Highly adaptable, safe, versatile	Complex control, bulky	Low to Medium	Flexible materials, elastomers	Low to Moderate	
Electro-hydrodynamics (EHD)[44]	Non-contact, suitable for delicate objects	Limited force, may require conductive surfaces	Low to Medium	Conductive fluids, dielectrics	Low to Moderate	
Microfluidic Actuation[45]	High precision, low energy consumption	Limited force, complex control	Low to Medium	Fluids, microfluidic channels	Moderate	
Optical Actuation[46]	Non-contact, precise, suitable for certain applications	Limited force, line of sight	Low to Medium	Light sources, photomechanical materials	Low to Moderate	
Magnetic Actuation[47]	Non-contact, precise, suitable for delicate objects	Limited force, requires magnetic materials	Low to Medium	Magnets, magnetic materials	Low to Moderate	
Piezoelectric Actuation[48]	Precise, compact, suitable for small-scale applications	Limited force, brittle components	Low to Medium	Piezoelectric materials, ceramics	Moderate	
Shape Memory Polymer Actuation[49]	Compact, adaptable, high strain	Limited force, slow response	Low to Medium	Shape-memory polymers	Low to Moderate	
Electrorheological Fluid Actuation[50]	High force when activated, adaptable	Complex control, viscous fluids	Medium to High	Electrorheological fluids	Moderate	
Mechanical Compliant Actuation[51]	Simple, reliable, low cost	Limited force, restricted applications	Low to Medium	Mechanical components	Low to Moderate	
Tendon-Driven Actuation[52]	Precise, versatile, high force output	Mechanical complexity, wear and tear	High	Cables, mechanical components	Moderate	
Fluidic Artificial Muscles[53]	High force-to-weight ratio, adaptable	Requires pressurized air source	High	Rubber-like materials, textiles	Moderate	

Commented [ra33]: B. Mosadegh, P. Polygerinos, C. Keplinger, S. Wennstedt, R. F. Shepherd, U. Gupta, J. Shim, K. Bertoldi, C. J.Walsh, , and G. M.Whitesides, ... [1]

Commented [ra34]: P. Moseley, J. M. Florez, H. A. Sonar, W. C. Gunjan Agarwal, and ... [2]

Commented [ra35]: Obaji M, Zhang S. Investigation into the force distribution mechanism ... [3]

Commented [ra36]: Liu M, Hao L, Zhang W, Zhao Z. A novel design of shape-memory ... [4]

Commented [ra37]: Xu L, Gu G. Bioinspired Venus flytrap: a dielectric elastomer actuated ... [5]

Commented [ra38]: Wang YZ, Gupta U, Parulekar N, Zhu J. A soft gripper of fast speed ... [6]

Commented [ra39]: G. Chen, X. Yang, X. Zhang, and H. Hu, "Water hydraulic soft actuators for underwater ... [7]

Commented [ra40]: X. Huang, Z. Ren and C. Majidi, "Soft Thermal Actuators with Embedded Liquid Metal ... [8]

Commented [ra41]: Yin H, Zhang X, Li J, Cao J. Grasping model and experiment of a ... [9]

Commented [ra42]: B. Mosadegh, P. Polygerinos, C. Keplinger, S. Wennstedt, R. F. Shepherd, ... [10]

Commented [ra43]: S. Shabaniverki, S. Xie, J. Ren, and J. Juarez, "Soft Ferrofluid Actuator Based on 3D-Printed ... [11]

Commented [ra44]: M. Ariyanto, M. Munadi, J. D. Setiawan, D. Mulyanto and T. Nugroho, "Three-Finge ... [12]

Commented [ra45]: J. Seyed-Yagoobi, "Electrohydrodynamic pumping of dielectric liquids," ... [13]

Commented [ra46]: Run Ze Gao, Carolyn L. Ren; Synergizing microfluidics with soft robotics: A perspe ... [14]

Commented [ra47]: H. Guo, A. Priimagi, and H. Zeng, "Optically Controlled Latching and Launching in Soft ... [15]

Commented [ra48]: H. Wang, Z. Zhu, H. Jin, R. Wei, L. Bi, and W. Zhang, "Magnetic Soft Robots: Design, Actuat ... [16]

Commented [ra49]: Lu, J., Miao, Z., Wang, Z. *et al.* Piezoelectric soft robot driven by mechanical energy. ... [17]

Commented [ra50]: X. Wei *et al.*, "Shape Memory Polymer-based Stiffness Variable Soft Actuator Via Di ... [18]

Commented [ra51]: T. Huang, D. Xu, H. Zhang, O. Bai, A. Aravelli, X. Zhou, and B. Han, "A lightweight flexible s ... [19]

Commented [ra52]: L. A. Páramo-Carranza, A. Lopez-González, Juan C. Tejada, "Compliant Mechanism Sof ... [20]

Commented [ra53]: N. Tan, X. Gu, and H. Ren, "Design, characterization and applications of a novel soft actu ... [21]

Commented [ra54]: J. Garbulinski and N. M. Wereley, "Bending Properties of an Extensile Fluidic Artificial M ... [22]

Ionic Polymer-Metal Composite Actuators (IPMC)[54]	Lightweight, soft, versatile, low power consumption	Limited force, durability	Low to Medium	Ionic polymer-metal composites	Moderate
Soft Pneumatic Artificial Skin[55]	Tactile feedback, adaptable, safe	Limited to sensory tasks	Low to Medium	Flexible materials, elastomers	Low to Moderate

Table: Response Time of Various Actuator

Response Time	Types of Actuators	Ref.
Fast	Pneumatic Actuation, Vacuum Actuation	
Medium[56]	Cable-Driven Actuation, Electroactive Polymer Actuation, Electro-adhesive Actuation, Hydraulic Actuation, Pneumatic Artificial Muscles (PAMs), Soft Fluidic Actuators, Ferrofluid-Based Actuation, Soft Pneumatic Networks, Electro-hydrodynamics (EHD), Microfluidic Actuation, Optical Actuation, Magnetic Actuation, Piezoelectric Actuation, Electrorheological Fluid Actuation, Mechanical Compliant Actuation, Tendon-Driven Actuation, Fluidic Artificial Muscles, Ionic Polymer-Metal Composite Actuators (IPMC), Soft Pneumatic Artificial Skin	
Slow	Shape Memory Alloy Actuation	
Medium to Slow	Thermal Actuation	
Slow to Medium	Shape Memory Polymer Actuation	

5 Soft Gripper Sensors

Type of Sensor	**Working Principle**	**Measurement**	**Advantage**	**Limitation**
Resistive Ionic	Change in electrical resistance due to the movement of ions in a liquid or gel.	Liquid or gel level, concentration, and density.	Low cost and simple to use.	Not very accurate and can be affected by temperature.
Piezoelectric	Generation of an electrical charge when the sensor is subjected to mechanical stress.	Force, pressure, and acceleration.	High sensitivity and accuracy.	Expensive and fragile.
Piezoresistive	Change in electrical resistance due to mechanical stress.	Force, pressure, and **acceleration**.	Low cost and durable.	Not as sensitive as piezoelectric sensors.
Piezocapacitive Strain	Change in capacitance due to mechanical stress.	Strain, pressure, and acceleration.	High sensitivity and accuracy.	Expensive and fragile.
Flexible Electronics	Use of flexible materials to create sensors.	A variety of measurements, including strain, pressure, temperature, and chemical concentration.	Lightweight and conformable to curved surfaces.	Not as durable as traditional sensors.
Capacitive Strain	Change in capacitance due to the change in distance between two electrodes.	Strain, pressure, and displacement.	High sensitivity and accuracy.	It can be affected by environmental factors such as moisture and dust.
Conductive Thermoplastic Resistive Strain	Change in electrical resistance due to the change in	Strain, temperature, and pressure.	Low cost and durable.	Not as sensitive as other strain sensors.

Commented [ra55]: H. Zhang, Z. Lin, Y. Hu, S. Ma, Y. Liang, L. Ren, and L. Ren, "Low-Voltage Driven Ionic Polymer-Metal Composite Actuators: Structures, Materials, and Applications," *Advanced Science*, vol. 10, no. 2, p. 2206135, Jan. 2023.
DOI: 10.1002/advs.202206135

Commented [ra56]: S. Joe, M. Totaro, H. Wang, and L. Beccai, "Development of the Ultralight Hybrid Pneumatic Artificial Muscle: Modelling and optimization," *PLoS ONE*, vol. 16, no. 4, p. e0250325, Apr. 2021.
DOI: 10.1371/journal.pone.0250325

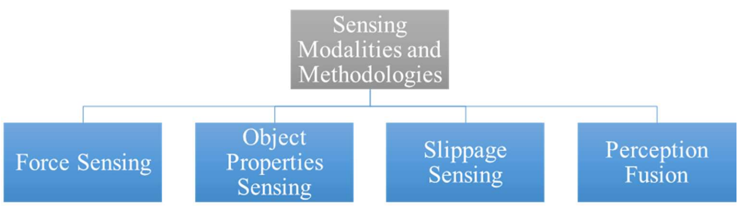
Commented [ra57]: Samadikhoshkho Z, Zareinia K, Janabi-Sharifi F. A brief review on
robotic grippers classifications. 2019 IEEE Can Conf Electr Comput Eng CCECE 2019;2019:10–13

	temperature of a conductive thermoplastic material.			
Optical Sensing	Use of light to measure various physical and chemical properties.	A variety of measurements, including strain, pressure, temperature, and chemical concentration.	Non-contact and can be used in hazardous environments.	It can be expensive and complex.
Strain Sensitive Textiles and Fibers	Use of textiles and fibers to create strain sensors.	Strain, pressure, and movement.	Lightweight and conformable to curved surfaces.	Not as durable as traditional sensors.

#Technology-1, Table 4

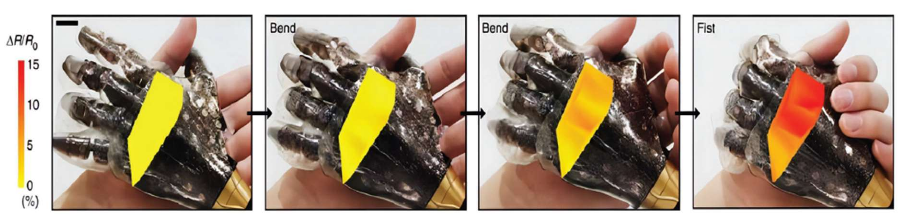
#Material-2 (Haptic system)

#Material-3, Table 2



Force Sensing:

Force sensing is critical in the design and operation of soft grippers and robotic systems. These sensing modalities are critical because they allow for efficient grasping activities and safe interactions with the environment. Because force sensing allows them to dynamically adjust their grasping force and posture, soft grippers are highly adaptable, capable of handling objects of varying sizes and weights, and can even operate in challenging conditions such as low-light or underwater environments. Because of their stability, user-friendliness, and cost-effectiveness, commercial tactile sensors are routinely integrated into soft grippers. These sensors aid in job performance by precisely monitoring contact force and direction. Some soft grippers, for example, have six-axis force/torque sensors in their fingertips.



[57]

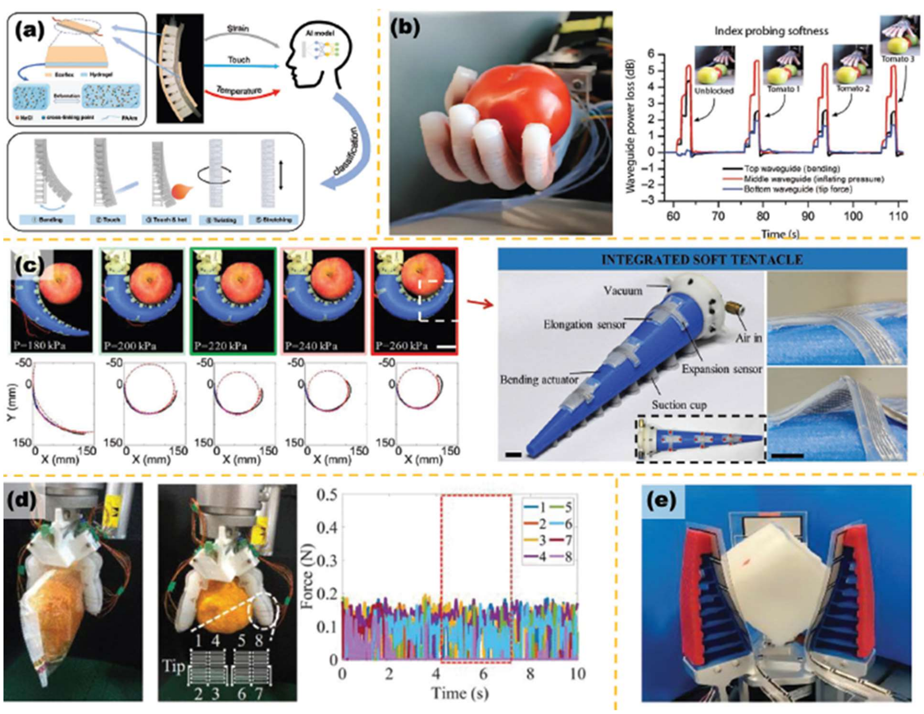
Commented [ra58]: J. Kim, M. Lee, H. J. Shim, R. Ghaffari, H. R. Cho, D. Son, Y. H. Jung, M. Soh, C. Choi, S. Jung, K. Chu, D. Jeon, S.-T. Lee, J. H. Kim, S. H. Choi, T. Hyeon, D.-H. Kim, Nat. Commun. 2014, 5, 5747

Fig: Sequential images of prosthetic hand performing handshake. Scale bar, 2 cm. Spatio-temporal maps of resistance change of SiNR strain gauge arrays are overlapped at the corresponding locations on the back of hand. [Reference][58] Copyright 2014, Nature Publishing Group

Commented [ra59]: Chen, Z., Min, H., Wang, D., Xia, Z., Sun, F., & Fang, B. (2023, July 24). *A Review of Myoelectric Control for Prosthetic Hand Manipulation*. Biomimetics; Multidisciplinary Digital Publishing Institute. https://doi.org/10.3390/biomimetics8030328

This field is dominated by two basic gripping strategies. The first method is a reactive grasping strategy, in which the clutching action is initiated based on tactile feedback. The second method is a standard predictive strategy that starts grabbing by predicting the gripper's point of contact with the object. Empirical evidence supports the improved grasp robustness produced by using tactile sensor feedback. Capacitive sensors are frequently used in soft grippers, where they are integrated into the gripper's silicone covering. Distributed sensing nodes are also utilized to collect preparatory data on the items to be grasped. MEMS microgrippers, which combine capacitive force sensors and electrostatic actuators, provide high-resolution force measuring capabilities, ensuring precise force detection.

Objects Property Sensing:



[54], [55], [56], [57]Figure 7, various tactile sensing technologies for object properties are depicted: a) Hydrogel sensors and machine learning enable the discrimination of thermal stimuli and mechanical deformations in soft actuators. [Source: Reproduced with permission from Wiley, Copyright 2022.] b) A soft prosthetic hand with optoelectronic innervation achieved via stretchable optical waveguides. [Source: Reproduced with permission from AAAS, Copyright 2016.] c) The figure shows a proprioceptive soft tentacle gripper featuring crosswise stretchable sensors. [Source: Reproduced with permission from IEEE, Copyright 2020.] d) A soft gripper is equipped with

microfluidic tactile sensors for the classification of deformable objects. [Source: Reproduced with permission from IEEE, Copyright 2022.] e) Object recognition for variable stiffness objects is accomplished with a CNN-Bayes approach.[59], [60], [61], [62]

Commented [ra60]: 1. Z. Sun, S. Wang, Y. Zhao, Z. Zhong, L. Zuo, *Adv. Intell. Syst.* **2022**, 2200089.
2. H. Zhao, K.O'Brien, S. Li, R. F. Shepherd, *Sci. Rob.* **2016**, *1*, eaai7529
3. Z. Xie, F. Yuan, Z. Liu, Z. Sun, E. M. Knubben, L. Wen, *IEEE/ASME Trans. Mechatron.* **2020**, *25*, 1841.
4. Y. Khan, A. Thielens, S. Muin, J. Ting, C. Baumbauer, A. C. Arias, Adv. Mater. 2020, 32, 1905279

The creation of electroactive polymer tactile pressure sensors, which are distinguished by their robustness, sensitivity, and high-resolution measurements even at extremely low pressures. Fiber Bragg Gratings (FBGs) are used for precise force measurement in difficult conditions such as those involving impact, electromagnetic interference, vibration, and severe temperatures. Furthermore, vision-based techniques are popular in force sensing due to their advantages such as rich sensing data, high resolution, and low cost. Some sensors are particularly good at determining contact force distributions using observation and numerical methods.

For safe and proficient manipulation in the field of robotic soft grippers, object characteristics acquisition is essential. Sensation of touch is essential for accurately classifying properties such as size, shape, stiffness, hardness, roughness, and texture, allowing for self-sufficient and damage-free grabbing. Numerous tactile sensors have been created, such as EGaIn curvature sensors in soft grippers with variable effective lengths (VELS) and conductive thermoplastic polyurethane (TPU) for position feedback. To precisely identify these attributes, sensor arrays—such as a roughness identification sensor that makes use of Fiber Bragg Gratings (FBG)—are used in conjunction with machine learning (ML) approaches. Robotic grippers also use FBGs to detect stiffness and object size. Five-fingered grippers with uSkin tactile sensors provide accurate and exact identification of typical objects. Variable-stiffness objects are identified using a three-finger soft gripper equipped with force-sensitive resistors. GelSight tactile sensors can only approximate an object's hardness. A machine learning algorithm classifies the dual stretchable hydrogel sensors in a soft finger, which provide proprioception and multimodal sensing. With these developments, robotic soft grippers can perform better in a range of scenarios.

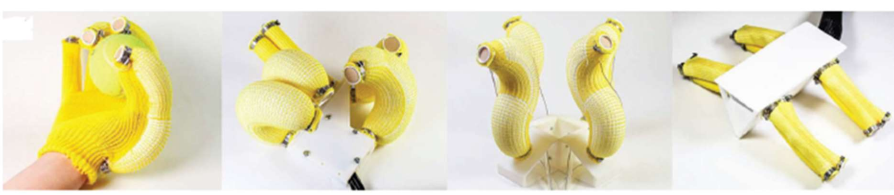


Fig:

Slipping Sense:

In the domain of soft robotics, the detection of slip is of utmost importance in order to ensure the maintenance of a solid grip. Various innovative approaches have been devised to effectively cater to this requirement. The utilization of a thin piezoelectric film within an underwater soft gripper is one method that involves the creation of charge during deformation to facilitate slip detection through vibration. Fiber Bragg Gratings (FBGs) have been effectively utilized for slip detection through the analysis of wavelength shifts. The successful prediction of slips has been achieved by the integration of distributed sensor arrays and machine learning approaches, specifically the utilization of SynTouch BioTac sensors in conjunction with machine learning algorithms. This approach capitalizes on the abundance of tactile data to enhance slip prediction capabilities.

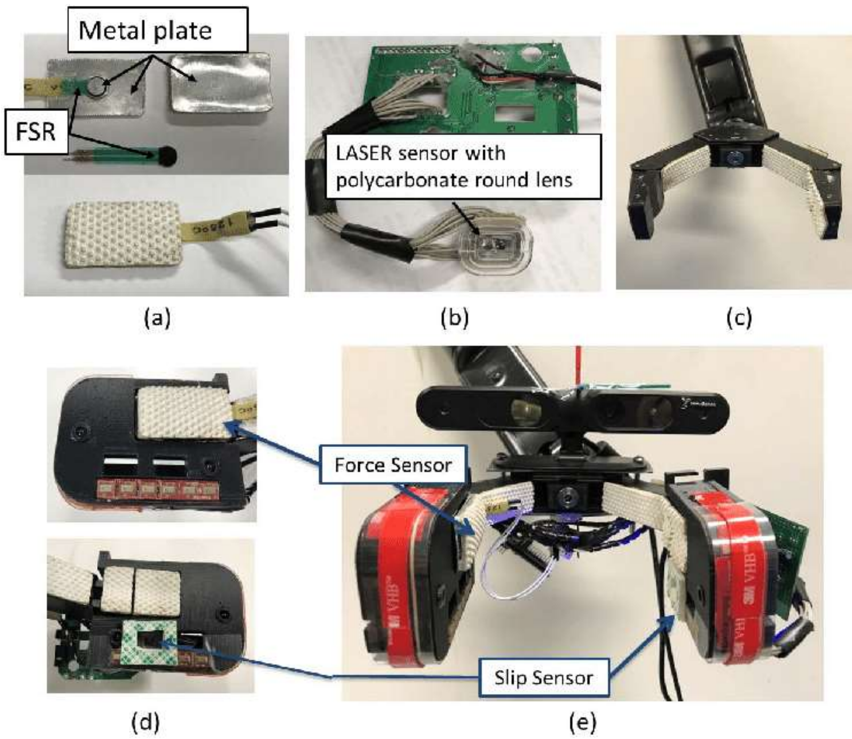


Fig: An Adaptive Control-Based Approach for 1-Click Gripping of Novel Objects Using a Robotic Manipulator with slip sensor for avoiding slipping of the object piece [Reference][63]

Commented [ra61]: An Adaptive Control-Based Approach for 1-Click Gripping of Novel Objects Using a Robotic Manipulator
April 2018IEEE Transactions on Control Systems Technology PP(99):1-8
DOI:10.1109/TCST.2018.2821651

In addition, the utilization of vision-based tactile sensors, such as GelSight, has been implemented in slip detection tasks by means of analyzing object motion and slip through image analysis techniques. The application of deep learning, namely deep neural networks (DNN) and support vector machines (SVM), has demonstrated potential in effectively categorizing slip occurrences in the field of soft robotics, resulting in notable levels of accuracy in detection. The implementation of advanced slip detection techniques significantly improves the stability and dependability of soft robotic systems, hence enabling secure manipulation of objects in diverse application domains.

Perception Fusion:

Sensor fusion is necessary in soft robotics to get over the drawbacks of using just one type of sensing, such as touch. Intelligent soft grippers use several sensors to improve grabbing and object recognition, drawing inspiration from human perception. Jia et al. presented a multimodal SF-RNN model that used tactile sensor modalities such as vibration, internal fluid pressure, and fingerpad deformation to reach an astounding 98.7% test accuracy. Another innovation for real-time object topography, stiffness, and odor collection is a tactile-olfactory sensing array with high-sensitivity silicon-based force and gas sensors, inspired by the star-nosed mole.

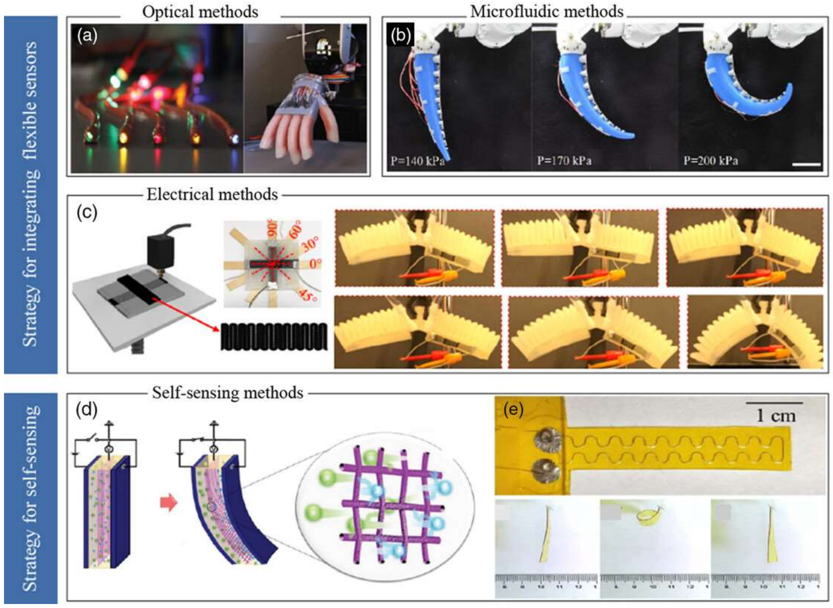


Fig: Soft robots with advanced bending perception: a) Fiber-reinforced hands with optical strain sensors. [AAAS, 2016] b) Liquid metal microfluidic sensors in pneumatic hands. [IEEE, 2020] c) Pneumatic grippers with active material strain sensors. [ACS, 2020] d) Self-sensing ion actuator for bending perception. [Wiley-VCH, 2019] e) Electrothermal actuator improves bending perception. [IEEE, 2021] [60], [61], [64], [65], [66]

Commented [ra62]: 1. H. Zhao, K. O'Brien, S. Li, R. F. Shepherd, *Sci. Robot.* 2016, 1, eaai7529.
2. Z. Xie, F. Yuan, Z. Liu, Z. Sun, E. M. Knubben, L. Wen, *IEEE ASME Trans. Mechatron.* 2020, 25, 1841.
3. S. Mousavi, D. Howard, F. Zhang, J. Leng, C. H. Wang, *ACS Appl. Mater. Interfaces* 2020, 12, 15631.
4. R. Tabassian, V. H. Nguyen, S. Umrao, M. Mahato, J. Kim, M. Porfiri, I. K. Oh, *Adv. Sci.* 2019, 6, 1901711
5. Y. Cao, J. Dong, *IEEE ASME Trans. Mechatron.* 2021, 26, 854

With the invention of the flexible bimodal smart skin (FBSS) by Liu et al., humans can now train soft robots with just their hands and eyes by performing simultaneous tactile and touchless sensing. With FBSS installed, soft robotic grippers can "search and grasp" items using both touchless and tactile sensing. With an astounding 98.75% accuracy, a triboelectric-inductive hybrid tactile sensor was created for precise item recognition, recognizing eight distinct fruits. These developments in sensor fusion enable soft robots to engage with their environment more successfully and carry out intricate tasks with increased precision.

6 Discussions

Limitations of this Review

7 Conclusion:

key findings of the review

future directions of soft grippers for ADLs

References

[1] J. Kim, J. W. Kim, H. C. Kim, L. Zhai, H.-U. Ko, and R. M. Muthoka, “Review of Soft Actuator Materials,” *Int. J. Precis. Eng. Manuf.*, vol. 20, no. 12, pp. 2221–2241, Dec. 2019, doi: 10.1007/s12541-019-00255-1.

[2] Ankit, T. Y. K. Ho, A. Nirmal, M. R. Kulkarni, D. Accoto, and N. Mathews, “Soft Actuator Materials for Electrically Driven Haptic Interfaces,” *Adv. Intell. Syst.*, vol. 4, no. 2, p. 2100061, Feb. 2022, doi: 10.1002/aisy.202100061.

[3] Y. Hao, S. Zhang, B. Fang, F. Sun, H. Liu, and H. Li, “A Review of Smart Materials for the Boost of Soft Actuators, Soft Sensors, and Robotics Applications,” *Chin. J. Mech. Eng.*, vol. 35, no. 1, p. 37, Dec. 2022, doi: 10.1186/s10033-022-00707-2.

[4] A. Hassan, F. Aljaber, H. Godaba, I. Vitanov, and K. Althoefer, “Soft Multi-point Waveguide Sensor for Proprioception and Extereoception in Inflatable Fingers,” in *2021 IEEE 6th International Forum on Research and Technology for Society and Industry (RTSI)*, Naples, Italy: IEEE, Sep. 2021, pp. 574–579. doi: 10.1109/RTSI50628.2021.9597247.

[5] J. F. Elfferich, D. Dodou, and C. D. Santina, “Soft Robotic Grippers for Crop Handling or Harvesting: A Review,” *IEEE Access*, vol. 10, pp. 75428–75443, 2022, doi: 10.1109/ACCESS.2022.3190863.

[6] T. Wang *et al.*, “Smart Composite Hydrogels with pH-Responsiveness and Electrical Conductivity for Flexible Sensors and Logic Gates,” *Polymers*, vol. 11, no. 10, p. 1564, Sep. 2019, doi: 10.3390/polym11101564.

[7] H. Chung, A. M. Parsons, and L. Zheng, “Magnetically Controlled Soft Robotics Utilizing Elastomers and Gels in Actuation: A Review,” *Adv. Intell. Syst.*, vol. 3, no. 3, p. 2000186, Mar. 2021, doi: 10.1002/aisy.202000186.

[8] Y. Lee, J. Choi, Y. Choi, S. M. Park, and C. Yoon, “Four-Dimensional Printing of Stimuli-Responsive Hydrogel-Based Soft Robots,” *J. Vis. Exp.*, no. 191, p. 64870, Jan. 2023, doi: 10.3791/64870-v.

[9] J. Meng *et al.*, “Novel Environmentally Responsive Polyvinyl Polyamine Hydrogels Capable of Phase Transformation with Temperature for Applications in Reservoir Profile Control,” *Gels*, vol. 9, no. 12, p. 950, Dec. 2023, doi: 10.3390/gels9120950.

[10] B. Strachota *et al.*, “Exceptionally Fast Temperature-Responsive, Mechanically Strong and Extensible Monolithic Non-Porous Hydrogels: Poly(N-isopropylacrylamide) Intercalated with Hydroxypropyl Methylcellulose,” *Gels*, vol. 9, no. 12, p. 926, Nov. 2023, doi: 10.3390/gels9120926.

[11] Y. Ding *et al.*, “Preparation of Photo-responsive DNA Supramolecular Hydrogels and Their Application as UV Radiometers,” *Chem. Res. Chin. Univ.*, vol. 39, no. 1, pp. 115–120, Feb. 2023, doi: 10.1007/s40242-023-2329-5.

[12] Z. J. Wang, C. Y. Li, X. Y. Zhao, Z. L. Wu, and Q. Zheng, “Thermo- and photo-responsive composite hydrogels with programmed deformations,” *J. Mater. Chem. B*, vol. 7, no. 10, pp. 1674–1678, 2019, doi: 10.1039/C8TB02896F.

[13] J. Shintake, V. Cacucciolo, D. Floreano, and H. Shea, “Soft Robotic Grippers,” *Adv. Mater.*, vol. 30, no. 29, p. 1707035, Jul. 2018, doi: 10.1002/adma.201707035.

[14] R. G. Fiddian-Green and W. Silen, “Mechanisms of disposal of acid and alkali in rabbit duodenum,” *Am. J. Physiol.*, vol. 229, no. 6, pp. 1641–1648, Dec. 1975, doi: 10.1152/ajplegacy.1975.229.6.1641.

[15] A. K. Nguyen *et al.*, “A Tri-Stable Soft Robotic Finger Capable of Pinch and Wrap Grasps,” in *2020 IEEE International Conference on Robotics and Automation (ICRA)*, Paris, France: IEEE, May 2020, pp. 9028–9034. doi: 10.1109/ICRA40945.2020.9196818.

[16] W. Park, S. Seo, and J. Bae, “A Hybrid Gripper With Soft Material and Rigid Structures,” *IEEE Robot. Autom. Lett.*, vol. 4, no. 1, pp. 65–72, Jan. 2019, doi: 10.1109/LRA.2018.2878972.

[17] Y. Shapiro, A. Wolf, and K. Gabor, “Bi-bellows: Pneumatic bending actuator,” *Sens. Actuators Phys.*, vol. 167, no. 2, pp. 484–494, Jun. 2011, doi: 10.1016/j.sna.2011.03.008.

[18] E. H. Skorina *et al.*, “Reverse pneumatic artificial muscles (rPAMs): Modeling, integration, and control,” *PLOS ONE*, vol. 13, no. 10, p. e0204637, Oct. 2018, doi: 10.1371/journal.pone.0204637.

[19] M. Kotal, R. Tabassian, S. Roy, S. Oh, and I. Oh, “Metal–Organic Framework-Derived Graphitic Nanoribbons Anchored on Graphene for Electroionic Artificial Muscles,” *Adv. Funct. Mater.*, vol. 30, no. 29, p. 1910326, Jul. 2020, doi: 10.1002/adfm.201910326.

[20] H. Zhao, Y. Li, A. Elsamadisi, and R. Shepherd, “Scalable manufacturing of high force wearable soft actuators,” *Extreme Mech. Lett.*, vol. 3, pp. 89–104, Jun. 2015, doi: 10.1016/j.eml.2015.02.006.

[21] J. Shintake, V. Cacucciolo, D. Floreano, and H. Shea, “Soft Robotic Grippers,” *Adv. Mater.*, vol. 30, no. 29, p. 1707035, Jul. 2018, doi: 10.1002/adma.201707035.

[22] L. Gerez and M. Liarokapis, “A Pneumatically Driven, Disposable, Soft Robotic Gripper Equipped with Retractable, Telescopic Fingers,” in *2020 8th IEEE RAS/EMBS International Conference for Biomedical Robotics and Biomechatronics (BioRob)*, New York City, NY, USA: IEEE, Nov. 2020, pp. 36–41. doi: 10.1109/BioRob49111.2020.9224292.

[23] I. Hussain *et al.*, “Compliant gripper design, prototyping, and modeling using screw theory formulation,” *Int. J. Robot. Res.*, vol. 40, no. 1, pp. 55–71, Jan. 2021, doi: 10.1177/0278364920947818.

[24] M. Yu *et al.*, “A self-sensing soft pneumatic actuator with closed-Loop control for haptic feedback wearable devices,” *Mater. Des.*, vol. 223, p. 111149, Nov. 2022, doi: 10.1016/j.matdes.2022.111149.

[25] C. Rad, O. Hancu, and C. Lapusan, “Data-Driven Kinematic Model of PneuNets Bending Actuators for Soft Grasping Tasks,” *Actuators*, vol. 11, no. 2, p. 58, Feb. 2022, doi: 10.3390/act11020058.

[26] G. Stano, L. Arleo, and G. Percoco, “Additive Manufacturing for Soft Robotics: Design and Fabrication of Airtight, Monolithic Bending PneuNets with Embedded Air Connectors,” *Micromachines*, vol. 11, no. 5, p. 485, May 2020, doi: 10.3390/mi11050485.

[27] X. Zhang *et al.*, “A Modular Soft Gripper with Combined Pneu-Net Actuators,” *Actuators*, vol. 12, no. 4, p. 172, Apr. 2023, doi: 10.3390/act12040172.

[28] H. Su *et al.*, “Pneumatic Soft Robots: Challenges and Benefits,” *Actuators*, vol. 11, no. 3, p. 92, Mar. 2022, doi: 10.3390/act11030092.

[29] B. Zhang, C. Hu, P. Yang, Z. Liao, and H. Liao, “Design and Modularization of Multi-DoF Soft Robotic Actuators,” *IEEE Robot. Autom. Lett.*, vol. 4, no. 3, pp. 2645–2652, Jul. 2019, doi: 10.1109/LRA.2019.2911823.

[30] M. Wehner *et al.*, “An integrated design and fabrication strategy for entirely soft, autonomous robots,” *Nature*, vol. 536, no. 7617, pp. 451–455, Aug. 2016, doi: 10.1038/nature19100.

[31] C. Lee *et al.*, “Soft robot review,” *Int. J. Control Autom. Syst.*, vol. 15, no. 1, pp. 3–15, Feb. 2017, doi: 10.1007/s12555-016-0462-3.

[32] W. Park, S. Seo, and J. Bae, “A Hybrid Gripper With Soft Material and Rigid Structures,” *IEEE Robot. Autom. Lett.*, vol. 4, no. 1, pp. 65–72, Jan. 2019, doi: 10.1109/LRA.2018.2878972.

[33] B. Mosadegh *et al.*, “Pneumatic Networks for Soft Robotics that Actuate Rapidly,” *Adv. Funct. Mater.*, vol. 24, no. 15, pp. 2163–2170, Apr. 2014, doi: 10.1002/adfm.201303288.

[34] P. Moseley, J. M. Florez, H. A. Sonar, G. Agarwal, W. Curtin, and J. Paik, “Modeling, Design, and Development of Soft Pneumatic Actuators with Finite Element Method,” *Adv. Eng. Mater.*, vol. 18, no. 6, pp. 978–988, Jun. 2016, doi: 10.1002/adem.201500503.

[35] Michael. O. Obaji and S. Zhang, “Investigation into the force distribution mechanism of a soft robot gripper modeled for picking complex objects using embedded shape memory alloy actuators,” in *2013 6th IEEE Conference on Robotics, Automation and Mechatronics (RAM)*, Manila, Philippines: IEEE, Nov. 2013, pp. 84–90. doi: 10.1109/RAM.2013.6758564.

[36] M. Liu, L. Hao, W. Zhang, and Z. Zhao, “A novel design of shape-memory alloy-based soft robotic gripper with variable stiffness,” *Int. J. Adv. Robot. Syst.*, vol. 17, no. 1, p. 1729881420907813, Jan. 2020, doi: 10.1177/1729881420907813.

[37] L. Xu and G. Gu, “Bioinspired Venus flytrap : A dielectric elastomer actuated soft gripper,” in *2017 24th International Conference on Mechatronics and Machine Vision in Practice (M2VIP)*, Auckland: IEEE, Nov. 2017, pp. 1–3. doi: 10.1109/M2VIP.2017.8211523.

[38] Y. Wang, U. Gupta, N. Parulekar, and J. Zhu, “A soft gripper of fast speed and low energy consumption,” *Sci. China Technol. Sci.*, vol. 62, no. 1, pp. 31–38, Jan. 2019, doi: 10.1007/s11431-018-9358-2.

[39] G. Chen, X. Yang, X. Zhang, and H. Hu, “Water hydraulic soft actuators for underwater autonomous robotic systems,” *Appl. Ocean Res.*, vol. 109, p. 102551, Apr. 2021, doi: 10.1016/j.apor.2021.102551.

[40] X. Huang, Z. Ren, and C. Majidi, “Soft Thermal Actuators with Embedded Liquid Metal Microdroplets for Improved Heat Management,” in *2020 3rd IEEE International Conference on Soft Robotics (RoboSoft)*, New Haven, CT, USA: IEEE, May 2020, pp. 367–372. doi: 10.1109/RoboSoft48309.2020.9115972.

[41] H. Yin, X. Zhang, J. Li, and J. Cao, “Grasping model and experiment of a soft robot gripper with variable stiffness,” in *2017 IEEE International Conference on Cybernetics and Intelligent Systems (CIS) and IEEE Conference on Robotics, Automation and Mechatronics (RAM)*, Ningbo: IEEE, Nov. 2017, pp. 134–139. doi: 10.1109/ICCIS.2017.8274762.

[42] S. Shabaniverki, S. Xie, J. Ren, and J. J. Juárez, “Soft Ferrofluid Actuator Based on 3D-Printed Scaffold Removal,” *3D Print. Addit. Manuf.*, vol. 8, no. 2, pp. 126–135, Apr. 2021, doi: 10.1089/3dp.2020.0012.

[43] M. Ariyanto, M. Munadi, J. D. Setiawan, D. Mulyanto, and T. Nugroho, “Three-Fingered Soft Robotic Gripper Based on Pneumatic Network Actuator,” in *2019 6th International Conference on Information Technology, Computer and Electrical Engineering (ICITACEE)*, Semarang, Indonesia: IEEE, Sep. 2019, pp. 1–5. doi: 10.1109/ICITACEE.2019.8904145.

[44] J. Seyed-Yagoobi, “Electrohydrodynamic pumping of dielectric liquids,” *J. Electrost.*, vol. 63, no. 6–10, pp. 861–869, Jun. 2005, doi: 10.1016/j.elstat.2005.03.047.

[45] R. Z. Gao and C. L. Ren, “Synergizing microfluidics with soft robotics: A perspective on miniaturization and future directions,” *Biomicrofluidics*, vol. 15, no. 1, p. 011302, Jan. 2021, doi: 10.1063/5.0036991.

[46] H. Guo, A. Priimagi, and H. Zeng, “Optically Controlled Latching and Launching in Soft Actuators,” *Adv. Funct. Mater.*, vol. 32, no. 17, p. 2108919, Apr. 2022, doi: 10.1002/adfm.202108919.

[47] H. Wang, Z. Zhu, H. Jin, R. Wei, L. Bi, and W. Zhang, “Magnetic soft robots: Design, actuation, and function,” *J. Alloys Compd.*, vol. 922, p. 166219, Nov. 2022, doi: 10.1016/j.jallcom.2022.166219.

[48] J. Lu *et al.*, “Piezoelectric soft robot driven by mechanical energy,” *Nano Res.*, vol. 16, no. 4, pp. 4970–4979, Apr. 2023, doi: 10.1007/s12274-022-5180-y.

[49] X. Wei *et al.*, “Shape Memory Polymer-based Stiffness Variable Soft Actuator Via Digital Light Processing-based 3D Printing,” in *2021 27th International Conference on Mechatronics and Machine Vision in Practice (M2VIP)*, Shanghai, China: IEEE, Nov. 2021, pp. 612–616. doi: 10.1109/M2VIP49856.2021.9665032.

[50] T. Huang *et al.*, “A lightweight flexible semi-cylindrical valve for seamless integration in soft robots based on the giant electrorheological fluid,” *Sens. Actuators Phys.*, vol. 347, p. 113905, Nov. 2022, doi: 10.1016/j.sna.2022.113905.

[51] L. A. Páramo-Carranza, A. Lopez-González, and J. C. Tejada, “Compliant Mechanism Soft Robot Design and Peristaltic Movement Optimization Using Random Search,” *J. Robot.*, vol. 2022, pp. 1–10, Apr. 2022, doi: 10.1155/2022/7562164.

[52] N. Tan, X. Gu, and H. Ren, “Design, characterization and applications of a novel soft actuator driven by flexible shafts,” *Mech. Mach. Theory*, vol. 122, pp. 197–218, Apr. 2018, doi: 10.1016/j.mechmachtheory.2017.12.021.

[53] J. Garbulinski and N. M. Wereley, “Bending Properties of an Extensile Fluidic Artificial Muscle,” *Front. Robot. AI*, vol. 9, p. 804095, Apr. 2022, doi: 10.3389/frobt.2022.804095.

[54] H. Zhang *et al.*, “Low-Voltage Driven Ionic Polymer-Metal Composite Actuators: Structures, Materials, and Applications,” *Adv. Sci.*, vol. 10, no. 10, p. 2206135, Apr. 2023, doi: 10.1002/advs.202206135.

[55] S. Joe, M. Totaro, H. Wang, and L. Beccai, “Development of the Ultralight Hybrid Pneumatic Artificial Muscle: Modelling and optimization,” *PLOS ONE*, vol. 16, no. 4, p. e0250325, Apr. 2021, doi: 10.1371/journal.pone.0250325.

[56] Z. Samadikhoshkho, K. Zareinia, and F. Janabi-Sharifi, “A Brief Review on Robotic Grippers Classifications,” in *2019 IEEE Canadian Conference of Electrical and Computer Engineering (CCECE)*, Edmonton, AB, Canada: IEEE, May 2019, pp. 1–4. doi: 10.1109/CCECE.2019.8861780.

[57] J. Kim *et al.*, “Stretchable silicon nanoribbon electronics for skin prosthesis,” *Nat. Commun.*, vol. 5, no. 1, p. 5747, Dec. 2014, doi: 10.1038/ncomms6747.

[58] Z. Chen, H. Min, D. Wang, Z. Xia, F. Sun, and B. Fang, “A Review of Myoelectric Control for Prosthetic Hand Manipulation,” *Biomimetics*, vol. 8, no. 3, p. 328, Jul. 2023, doi: 10.3390/biomimetics8030328.

[59] Z. Sun, S. Wang, Y. Zhao, Z. Zhong, and L. Zuo, “Discriminating Soft Actuators’ Thermal Stimuli and Mechanical Deformation by Hydrogel Sensors and Machine Learning,” *Adv. Intell. Syst.*, vol. 4, no. 9, p. 2200089, Sep. 2022, doi: 10.1002/aisy.202200089.

[60] H. Zhao, K. O’Brien, S. Li, and R. F. Shepherd, “Optoelectronically innervated soft prosthetic hand via stretchable optical waveguides,” *Sci. Robot.*, vol. 1, no. 1, p. eaai7529, Dec. 2016, doi: 10.1126/scirobotics.aai7529.

[61] B. Chen *et al.*, “Soft Origami Gripper with Variable Effective Length,” *Adv. Intell. Syst.*, vol. 3, no. 10, p. 2000251, Oct. 2021, doi: 10.1002/aisy.202000251.

[62] Y. Khan, A. Thielens, S. Muin, J. Ting, C. Baumbauer, and A. C. Arias, “A New Frontier of Printed Electronics: Flexible Hybrid Electronics,” *Adv. Mater.*, vol. 32, no. 15, p. 1905279, Apr. 2020, doi: 10.1002/adma.201905279.

[63] Z. Ding, N. Paperno, K. Prakash, and A. Behal, “An Adaptive Control-Based Approach for 1-Click Gripping of Novel Objects Using a Robotic Manipulator,” *IEEE Trans. Control Syst. Technol.*, vol. 27, no. 4, pp. 1805–1812, Jul. 2019, doi: 10.1109/TCST.2018.2821651.

[64] S. Mousavi, D. Howard, F. Zhang, J. Leng, and C. H. Wang, “Direct 3D Printing of Highly Anisotropic, Flexible, Constriction-Resistive Sensors for Multidirectional Proprioception in Soft Robots,” *ACS Appl. Mater. Interfaces*, vol. 12, no. 13, pp. 15631–15643, Apr. 2020, doi: 10.1021/acsami.9b21816.

[65] R. Tabassian *et al.*, “Graphene Mesh for Self-Sensing Ionic Soft Actuator Inspired from Mechanoreceptors in Human Body,” *Adv. Sci.*, vol. 6, no. 23, p. 1901711, Dec. 2019, doi: 10.1002/advs.201901711.

[66] Y. Cao and J. Dong, “Fabrication, modeling, and characterization of soft twisting electrothermal actuators with directly printed oblique heater,” *J. Micromechanics Microengineering*, vol. 32, no. 3, p. 035001, Mar. 2022, doi: 10.1088/1361-6439/ac4956.

Page 15: [1] Commented [ra33]	rana.me.kuet@gmail.com	10/26/2023 12:58:00 PM

B. Mosadegh, P. Polygerinos, C. Keplinger, S. Wennstedt, R. F. Shepherd,

U. Gupta, J. Shim, K. Bertoldi, C. J.Walsh, , and G. M.Whitesides,

“Pneumatic networks for soft robotics that actuate rapidly,” Advanced

functional materials, vol. 24, no. 15, pp. 2163–2170, 2014.

Page 15: [2] Commented [ra34]	rana.me.kuet@gmail.com	10/26/2023 12:59:00 PM

P. Moseley, J. M. Florez, H. A. Sonar, W. C. Gunjan Agarwal, and

J. Paik, “Modeling, design, and development of soft pneumatic actuators

with finite element method,” Advanced engineering materials, vol. 18,

no. 6, 2015.

Page 15: [3] Commented [ra35]	rana.me.kuet@gmail.com	10/26/2023 1:00:00 PM

Obaji M, Zhang S. Investigation into the force distribution mechanism

of a soft robot gripper modeled for picking complex objects

using embedded shape memory alloy actuators. 6th IEEE Conf.

Robot. Autom. Mechatronics. 2013

Page 15: [4] Commented [ra36]	rana.me.kuet@gmail.com	10/26/2023 1:02:00 PM

Liu M, Hao L, Zhang W, Zhao Z. A novel design of shape-memory

alloy-based soft robotic gripper with variable stiffness. Int J Adv

Robot Syst. 2020;17:1–12.

Page 15: [5] Commented [ra37]	rana.me.kuet@gmail.com	10/26/2023 1:03:00 PM

Xu L, Gu G. Bioinspired Venus flytrap: a dielectric elastomer actuated

soft gripper. 2017 24th Int Conf Mechatronics Mach Vis

Pract M2VIP 2017;2017:2017-Decem:1–3

Page 15: [6] Commented [ra38]	rana.me.kuet@gmail.com	10/26/2023 1:05:00 PM

Wang YZ, Gupta U, Parulekar N, Zhu J. A soft gripper of fast speed

and low energy consumption. Sci China Technol Sci. 2019;62:31–

8.

Page 15: [7] Commented [ra39]	rana.me.kuet@gmail.com	10/26/2023 1:07:00 PM

G. Chen, X. Yang, X. Zhang, and H. Hu, "Water hydraulic soft actuators for underwater autonomous robotic systems," *Applied Ocean Research*, vol. 112, p. 102551, 2021.

DOI: 10.1016/j.apor.2021.102551

Page 15: [8] Commented [ra40] **rana.me.kuet@gmail.com** **10/26/2023 1:09:00 PM**

X. Huang, Z. Ren and C. Majidi, "Soft Thermal Actuators with Embedded Liquid Metal Microdroplets for Improved Heat Management," *2020 3rd IEEE International Conference on Soft Robotics (RoboSoft)*, New Haven, CT, USA, 2020, pp. 367-372, doi: 10.1109/RoboSoft48309.2020.9115972.

Page 15: [9] Commented [ra41] **rana.me.kuet@gmail.com** **10/26/2023 1:10:00 PM**

Yin H, Zhang X, Li J, Cao J. Grasping model and experiment of a

soft robot gripper with variable stiffness. 2017 IEEE Int Conf

Cybern Intell Syst CIS 2017 IEEE Conf Robot Autom

Mechatronics, RAM 2017 - Proc 2018-Janua:134–139. 2017.

Page 15: [10] Commented [ra42] **rana.me.kuet@gmail.com** **10/26/2023 1:12:00 PM**

B. Mosadegh, P. Polygerinos, C. Keplinger, S. Wennstedt, R. F. Shepherd,

U. Gupta, J. Shim, K. Bertoldi, C. J.Walsh, , and G. M.Whitesides,

“Pneumatic networks for soft robotics that actuate rapidly,” Advanced

functional materials, vol. 24, no. 15, pp. 2163–2170, 2014.

Page 15: [11] Commented [ra43] **rana.me.kuet@gmail.com** **10/26/2023 1:15:00 PM**

S. Shabaniverki, S. Xie, J. Ren, and J. Juarez, "Soft Ferrofluid Actuator Based on 3D-Printed Scaffold Removal," *3D Printing and Additive Manufacturing*, vol. 8, no. 2, pp. 249-257, Feb. 2021.

DOI: 10.1089/3dp.2020.0012

Page 15: [12] Commented [ra44] **rana.me.kuet@gmail.com** **10/26/2023 1:16:00 PM**

M. Ariyanto, M. Munadi, J. D. Setiawan, D. Mulyanto and T. Nugroho, "Three-Fingered Soft Robotic Gripper Based on Pneumatic Network Actuator," *2019 6th International Conference on Information Technology, Computer and Electrical Engineering (ICITACEE)*, Semarang, Indonesia, 2019, pp. 1-5, doi: 10.1109/ICITACEE.2019.8904145.

Page 15: [13] Commented [ra45] **rana.me.kuet@gmail.com** **10/26/2023 1:22:00 PM**

J. Seyed-Yagoobi, "Electrohydrodynamic pumping of dielectric liquids," *Journal of Electrostatics*, vol. 63, no. 6-10, pp. 861-869, Jun. 2005.

DOI: 10.1016/j.elstat.2005.03.047

Page 15: [14] Commented [ra46] **rana.me.kuet@gmail.com** **10/26/2023 1:24:00 PM**

Run Ze Gao, Carolyn L. Ren; Synergizing microfluidics with soft robotics: A perspective on miniaturization and future directions. *Biomicrofluidics* 1 January 2021; 15 (1): 011302. https://doi.org/10.1063/5.0036991

Page 15: [15] Commented [ra47] **rana.me.kuet@gmail.com** **10/26/2023 1:27:00 PM**

H. Guo, A. Priimagi, and H. Zeng, "Optically Controlled Latching and Launching in Soft Actuators," *Advanced Functional Materials*, vol. 32, no. 21, p. 2108919, Jan. 2022.

DOI: 10.1002/adfm.202108919

Page 15: [16] Commented [ra48] **rana.me.kuet@gmail.com** **10/26/2023 1:28:00 PM**

H. Wang, Z. Zhu, H. Jin, R. Wei, L. Bi, and W. Zhang, "Magnetic Soft Robots: Design, Actuation, and Function," *Journal of Alloys and Compounds*, vol. 922, p. 166219, Nov. 2022.

DOI: 10.1016/j.jallcom.2022.16621

Page 15: [17] Commented [ra49]	rana.me.kuet@gmail.com	10/26/2023 1:30:00 PM

Lu, J., Miao, Z., Wang, Z. *et al.* Piezoelectric soft robot driven by mechanical energy. *Nano Res.* **16**, 4970–4979 (2023). https://doi.org/10.1007/s12274-022-5180-y

Download citation

Page 15: [18] Commented [ra50]	rana.me.kuet@gmail.com	10/26/2023 1:32:00 PM

X. Wei *et al*., "Shape Memory Polymer-based Stiffness Variable Soft Actuator Via Digital Light Processing-based 3D Printing," *2021 27th International Conference on Mechatronics and Machine Vision in Practice (M2VIP)*, Shanghai, China, 2021, pp. 612-616, doi: 10.1109/M2VIP49856.2021.9665032.

Page 15: [19] Commented [ra51]	rana.me.kuet@gmail.com	10/26/2023 1:34:00 PM

T. Huang, D. Xu, H. Zhang, O. Bai, A. Aravelli, X. Zhou, and B. Han, "A lightweight flexible semi-cylindrical valve for seamless integration in soft robots based on the giant electrorheological fluid," *Sensors and Actuators A: Physical*, vol. 347, p. 113905, Nov. 2022.

DOI: 10.1016/j.sna.2022.113905

Page 15: [20] Commented [ra52]	rana.me.kuet@gmail.com	10/26/2023 1:36:00 PM

L. A. Páramo-Carranza, A. Lopez-González, Juan C. Tejada, "Compliant Mechanism Soft Robot Design and Peristaltic Movement Optimization Using Random Search", *Journal of Robotics*, vol. 2022, Article ID 7562164, 10 pages, 2022. https://doi.org/10.1155/2022/7562164

Page 15: [21] Commented [ra53]	rana.me.kuet@gmail.com	10/26/2023 1:39:00 PM

N. Tan, X. Gu, and H. Ren, "Design, characterization and applications of a novel soft actuator driven by flexible shafts," *Mechanism and Machine Theory*, vol. 122, pp. 197-218, Apr. 2018.

DOI: 10.1016/j.mechmachtheory.2017.12.021

Page 15: [22] Commented [ra54]	rana.me.kuet@gmail.com	10/26/2023 2:53:00 PM

J. Garbulinski and N. M. Wereley, "Bending Properties of an Extensile Fluidic Artificial Muscle," *Frontiers in Robotics and AI*, vol. 9, p. 804095, Apr. 2022.

DOI: 10.3389/frobt.2022.80409