# Biomimetic Soft Hyper-Redundant Robotic Gripper: A Comprehensive Review

**Shubhashis Sanyal, Anuj Kumar Shukla*, Hrishi Sharad Pinjan, Piyush Tailor, Pyla Pavan Kumar, Suman Saurav, Surjeet Kumar Bhargav**

*Department of Mechanical Engineering, NIT Raipur*

*ssanyal.mech@nitrr.ac.in, akshukla.me@nitrr.ac.in*, hrishi662000@gmail.com, piyush1062000@gmail.com, pylapavan72@gmail.com, firebendersuman@gmail.com, bhargavsurjeetkumar@gmail.com*

## Abstract

Engineers have traditionally used rigid materials (such as hard plastics and metals) to build precise robotic systems that may be represented as a combination of rigid components joined at discrete points. However, designing robots inspired by natural systems consisting of continuous deformable materials should be equivalent to or even surpass the functionality of rigid robotic systems. These robots possess almost infinite degrees of freedom (DOF) and high levels of kinematic redundancy and are hence called hyper redundant robots. This paper describes the various types of soft hyper redundant robots, respective features, actuation mechanisms, sensors used in their control, and the future scope of hyper redundant robots in the field of robotics. We have shortlisted 200 papers based on keyword searching, namely soft robotics, pneumatic actuation, elastomers, bio-inspiration, bio-mimicry, universal gripper, etc. Further, the papers have been shortlisted using the paper's title, abstract, conclusions, and other details such as mathematical modelling, etc. This paper presents a comprehensive review of 116 articles covering the evolution of the topic, including the details of methodologies, design and analysis performed. This paper gives an overview of recent developments in soft robotics inspired from nature and their applications in gripping, inspection, medical field, etc. Challenges in designing soft robots include material modelling methods, incorporation of sensors and control.

**Keywords**. Hyper Redundant Robots, Soft Robotics, Gripper, Bio-mimetics.

## 1. INTRODUCTION

Soft robotics is a relatively new and under-researched field. Earlier, robots were always constructed using rigid components. The term "soft robot" was at the outset used in the 1950s to describe a rigid pneumatic hand with a degree of flexibility utilizing gas inside that could be compressed to offer compliance. The upcoming years saw more and more efforts being put into the soft robotics field because everyone soon realized the importance of flexibility.

Engineers have long been motivated by nature's beauty, and efficiency, and this fascination led to the development of bioinspired robots [1]. Such an attraction to nature has given birth to the development of soft hyper redundant robots. These robots have an almost infinite number of actuable degrees of freedom and possess high levels of kinematic redundancy.

These robots, morphologically and functionally similar to snakes, tendrils, elephant trunks, and tentacles, play a valuable role in tasks where reaching difficult places and interaction with delicate objects are required. Compared with rigid grippers, these grippers can grip/manipulate various objects from different directions where accessibility is a constraint [2], e.g., gripping an object placed inside a narrow passage.

Green plant vines covering huge land parts are a fascinating inspiration for soft hyper redundant robots used in inspection and exploration purposes. Such robots have numerous applications and can be used in the study of the environment. This can be done by attaching a camera on the tip of the tendril or vine-like modelled robots. Robots inspired by octopus tentacles like the octarm robots are used to move traffic divider cones from one location to another. These robots, also used by NASA, have found their application in inspection, lifting small objects and reaching restricted places [3]. Inspiration from plant root growth has also helped in the development of innovative hyper redundant actuators [4, 5].

The construction of soft robots has led to an increment in demand for alternative materials. These materials are highly deformable and stretchable, enabling the interaction of soft robots with delicate objects. These materials need to be checked for their tensile strength, strain and failure under different loading. For further development, additional knowledge of material behaviour is necessary and also a unified database of material constitutive models and experimental characterizations is of significant importance.

Actuation of these soft robots requires different actuators than those used in rigid link robots like pneumatic actuation [6, 7, 8], tendon-driven actuation [9] and actuation based on shape memory alloy (SMA) [10]. Most popular systems are based on pneumatic action using compressed gas. They provide significant mechanical output on little input energy while providing considerable flexibility, adaptability, cost effectiveness, lightweight, and safe human-robot interactions. Soft pneumatic robots based on flexible elastomers can consistently transfer pressure over broad areas without complicated controls, allowing them to operate fragile and irregular objects. Soft pneumatic actuators are being employed from space applications to medical applications, resulting from the breakthrough in material sciences and rapid prototyping [11]. A brief timeline of development in soft robotics can be seen in figure 1. Motor-based tendon-driven mechanisms are associated with unwieldy attachments resulting in the making of small and lightweight autonomous robotic systems difficult, and hence they have found little application. Meanwhile, the inherent softness of SMA actuators results in low actuation force and hence limits their application. They also require constant energy usage to keep the SMA at a certain temperature to maintain the appropriate deformation [12].

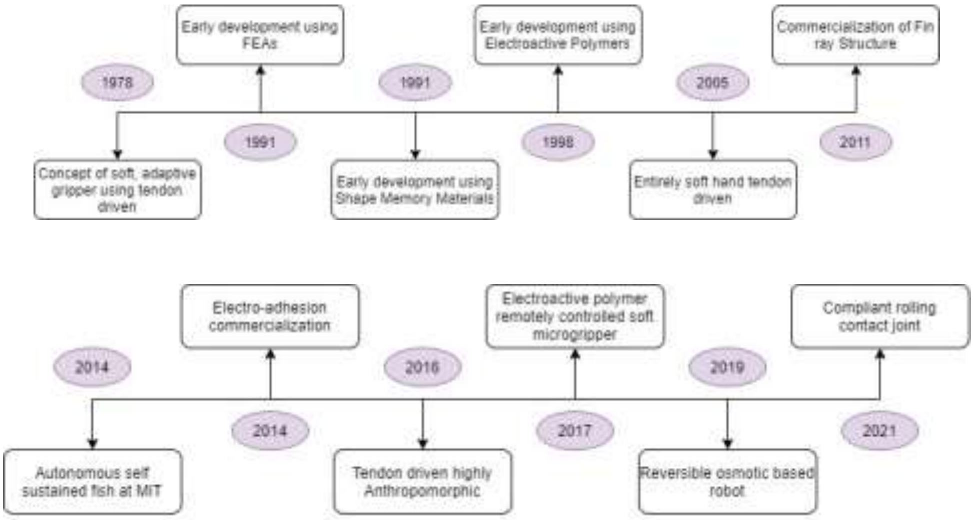

Figure 1. Timeline of developments in soft robotics

## 2. DESIGN

Engineers have traditionally looked to biology for inspiration when creating more sophisticated machines. The beauty and efficiency of nature greatly motivated engineers essayed at transferring ideas from biology to technology and specified it as biomimetics. There are several organisms from which the inspiration has been taken to mimic them in soft robotics, namely climbers, elephant's trunk, octopus tentacles, human fingers, fins of fishes, worms like caterpillars, Oligochaetes etc. as shown in figure 2, a brief summary of which is mentioned in Table 1.

Figure 2. Natural things from which inspirations have been taken, (i) octopus tentacles, (ii) elephant trunk (iii) caterpillar, (iv) tendril

Table 1. Various inspiration of soft robotic grippers and their applications

| S. No. | Inspiration | Applications |
|---|---|---|
| 1. | Octopus Tentacles | Holding different size object, inspection [3, 7, 16] |
| 2. | Snake | Inspection, locomotion, cleaning clogged tubes [29, 30, 31] |
| 3. | Elephant Trunk | Gripping heavy objects [32] |
| 4. | Human Finger | Compliant fingers to handle delicate objects [15, 26] |
| 5. | Climber | Inspection, exploration, gripping [20, 21] |
| 6. | Worms (caterpillar) | Locomotion, exploration [3, 17] |
| 7. | Plant roots | Soil penetration, search and rescue [5, 11] |

### *2.1. A 2-finger Gripper for grasping an unknown object*

Dexterous gripping is a recent difficulty in the field of robotics and automation. These grippers should be capable of grabbing various objects of varying sizes and forms. The shape of the gripper can also be put in as a restrain in the process of grasping. The associated hand configuration can be investigated using a probabilistic model to evaluate the inverse kinematics of the hand. To govern the locations and forces of joints and fingertips during task execution, grip synthesis algorithms must be used to control the grasping fingers. The process of developing a gripping configuration that fits a set of attributes important to the grasping action is referred to as grasp synthesis.

To construct this type of soft robotic gripper for two output port topology synthesis of compliant mechanism, a soft add scheme and an energy-based function are combined. The suggested gripper has two underactuated fingers, each of which is synthesized with the help of the recommended topology optimization method and designed using thermoplastic elastomer 3D printing. A general topologically optimized two-finger gripper has been made, which can hold objects of different shapes and sizes varying from a length of 42 mm to 141 mm and a limiting weight of 2.1 kg [3]. A similar type of gripper has been modelled and fabricated which deals with holding different types of fruits having a maximum payload capacity of 1.4 kg [5]. The detailed modelling of the gripper, which is supposed to hold unknown or irregular objects, has been described in [13, 14] . Universal grippers are also used to grasp unknown objects, and also new techniques are used to increase their application in different fields [15].

### *2.2. Octopus Tentacles inspired gripper*

Octopuses utilize their tapering tentacles to grasp their meal; inspired by this, a soft robotic tentacles gripper with suckers attached has been developed to grip the object tightly. Changing the taper angle of the conical shaped actuators gives a range of bending curves for the soft tentacle gripper. The conical-shaped actuators are also more flexible than the cylindrical actuators.

The variable bending curvature along the length of the tentacle is a curious and possibly beneficial phenomenon since it allows for the grabbing of much smaller items than those generally managed using non-tapered geometry. The pneumatic actuation plays a great role in actuating these grippers while having suction cups on the gripper ensures a proper hold of the gripper on the object. The whole design and their simulations along with the mathematical support, have been given in [3, 7, 16].

### *2.3. Worm, caterpillar, inspired soft robot*

Unlike other soft robots in development which require pneumatic or fluid actuation, these use shape-memory alloy micro coils or motor tendons for actuation. Different designs may be swiftly and cheaply created using elastomeric polymers or direct 3D printing because of the technology's versatility. Softworms can be constructed in any shape, but the emphasis is given to designs that don't require cumbersome assembly. In research paper [3, 17], the worm caterpillar's biology is discussed and their robotic models have been prepared and tested.

Research paper [18] suggests the usage of several modes of deformation and depicts a crawling robot with high deformability that employs deformation using compression and bending simultaneously. Inspired by the silkworm’s crawling gait motion, a compressive or bendable beam was proposed, further developed into a crawling robot. The simulation and prototype’s experimental results show that combining multiple deformation modes can help boost locomotion speed.

Origami has recently gained popularity as a way of creating compliant reconfigurable robots [19]. Using the programmable origami backbone, an open triangular spring model has been designed to provide stability and customizable elasticity that can be magnetically actuated to get the desired mobility. Its locomotion mechanism was similar to that of a caterpillar, in that it achieves directional motion by controlling body tension, which produces compressive stresses on the travelling surface. An extensive range of motion for travelling through varied terrains can be achieved by actuation based on the interaction between external and internal permanent magnets.

### *2.4. Bio-robotic tendril*

Climbing plants, with their fascinating intricacy and functional views, can be a substantial source of inspiration for biomimetic purposes. Climbing tendril-bear plants, for example, have an exciting technique of searching for grasping and climbing support, which can be explored and applied in future bio-inspired technologies. They can wrap around support to grasp, enabling it to obtain vertical displacement by single tendrils, which are filiform, irritable and lengthy organs. Tendrils characterize three primary motions; (i) Circumnutation: a natural movement that enhances the likelihood of finding support. (ii) Contact coiling: Curling of the tendril to grasp support, (iii) Free coiling: helical coiling of the tendril along its axis [20, 21]. The different phases in coiling are shown in figure 3. The tendril structure develops into two helical springs with opposite rotations starting from the linear configuration. The contraction or the evolution of the helical structure begins after the free coiling stage. Furthermore, the pulling effect is accomplished by forming an elastic spring-like attachment between the grabbed support, which can withstand highly strained situations like wind and loads. The tendril body is made up partially of G cells, a particular type of cells, which can dehydrate and increase the stiffness of the body, preventing uncoiling and this process is called lignification.

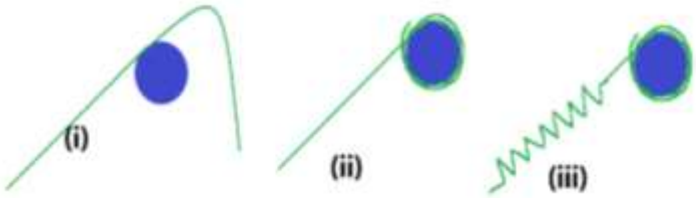

Figure 3. Phases in coiling (i) Circumnutation (ii) contact coiling (iii) free coiling.

The model for the vine-inspired continuum robot is adopted from computational biology in which circumnutation was interpreted as a kinematic model. The relation between the curvature change, orientation and longitudinal length along the perimeter is established [22]. The modelling of the tendril is done in two phases: the grasping part and the free coiling part. The free coiling part has been modelled as a helical spring, and the grasping part has been modelled as a continuum robot as a collection of ‘n’ linkages. Also, this model has been simulated in stimulation software, showing that free coiling and grasping are achieved. A detailed explanation has been given in [21].

The kinematic model was conceptualized and summarized using two main parts: (a) the Free coiling part, which is primarily dedicated to the free-coiling and pulling phase, (b) Grasping-Coiling part, which is primarily dedicated to the coiling and grasping phase. The GC component can be divided into separate pieces that move and bend when activated. The FC component that pulls can be thought of as an actuator that transforms a linear model to attain helical spring-like deformation [20]. Each sub-section of the GC portion was kinematically modelled and characterized using primary joints and the Denavit-Hartenberg (DH) parameters for modelling. The tendril’s grasping coiling can then be characterized using closed-form equations [21]. By relating actuator inputs like pneumatic pressure or tendon length to cartesian coordinates with the help of robot configuration coordinates, an approach for kinematic relationship is developed. This approach provides real-time shape and task control. It could be applied to a vast variety of continuum robots, also for bending individual sections [23, 24].

Tendril perversion was investigated on elastic rods using static Kirchoff equations. The model represents an elastic rod as a curve in the space with specific physical properties. The curve represents the axis and the rod’s parameters including orientation in space, stiffness, twist, and spin. The rod's external stresses, pressures, and moments are averaged over the filament's cross-sections. Differential growth has been used for intrinsic curvature in physical systems like tendril perversion. Kinematics of differential growth and the static solution for helix has been discussed in [25].

### 2.5. *Finger type gripper*

Relative stiffness allows the gripper to turn in the desired direction of the stiffer material. One hemispherical side is made more rigid and a cloth is stuffed to make it inextensible. This makes the inner part along which the finger curves. The model is being prototyped and tested with different weights. Increasing actuation pressure gives higher lifting force and grasping force. For a particular activation pressure, an increase in the finger's length decreases the generated pressure [15, 26].

Soft robotic gloves are also made to strengthen and support the muscles of the finger [27, 28]. Research is being done on soft robotic gloves that can be used to help people with functional grasp disorders with hand rehabilitation. These gloves are made from soft elastomers having great twisting and bending abilities.

### 2.6. *Continuum Robotics in medical surgery*

The current robotic systems and manipulators for medical applications are inspired by octopus tentacles, elephant trunks, snakes and many other creatures that can navigate limited areas, operate things in complicated settings, and follow curved trajectories in space. They can be used in different types of precision surgery because their small size and compliance are advantageous from a medical standpoint. Still, a lot of technological advancement in the field of sensing, control, and human-machine interaction is required [29, 30, 31].

### 2.7. *Elephant trunk inspired robots*

A manipulator with four sections using a hybrid cable and spring servo system actuation has been developed inspired by elephant trunks where it was assumed that an elephant trunk manipulator's sections bend into a circular arc with continuous curvature and an inextensible backbone. Similar trunk-like robots named ‘snake-arm robots’ have been made using cable tendon actuators with alternating stiff and soft discs to produce a bending backbone. Another elephant trunk-type manipulator was designed that consisted of a spiral tube looped around the manipulator backbone like a coil [32].

### 2.8. *Root inspired soil penetration robotic mechanism*

A kinematic model for growing robots was designed by inspiration from plant growth strategies. A 3D printer-like mechanism or tool were installed in the robot's tip, allows it to construct its body shape by using a sensor placed on the tip and a deposition head. It grows similarly to how a plant's root or shoot tip moves forward. Later, the simulation was done using simulation software and the positional and curvature errors were calculated between simulation results and practical results [11]. Also, another inspiration from root penetration is a working prototype design made up of a hollow cylinder, 3D-track (flexible cylindrical skin) and motor tendon skin actuation mechanism. It was observed in experiments that the use of this mechanism reduced the axial penetration force [5].

## 3. SOFT GRIPPING

Soft gripping is divided into three mechanisms: (i) actuation, (ii) variable stiffness, and (iii) variable adhesion. These three categories are not independent of each other, and many gadgets combine two or more classes to achieve greater performance.

### *3.1. Actuation*

### *3.1.1. Thermal responsive actuation (SMAs/ SMPs)*

Some polymers and alloys exhibit a shape memory attribute, where the material being temporarily deformed returns to an initial shape in response to a stimulus (typically heat). These materials are called Shape Memory Polymers (SMPs) or Shape Memory Alloys (SMAs) [33, 34]. These materials have found varied applications in the field of aerospace, medicine and robotics [35, 36, 37].

SMPs are made up of a polymer arrangement consisting of transition domains (TD) and elastic domains (ED). The TD softens (low stiffness) when the temperature is above the transition temperature, allowing the deformation of ED in response to force applied. As the temperature goes down, the TD gets stiff and averts the ED from deforming. When the material is heated again, the ED is released, and the object returns to its original state. This transition in SMPs happens due to a material phase change, in which crystallization-melting or vitrification-glass play a part. SMPs are frequently blended with other materials to increase properties such as strength, recovery force, and additional stimulus effects such as magnetic-active and electro-active effects [38]. Working cycle of SMA is shown in figure 4.

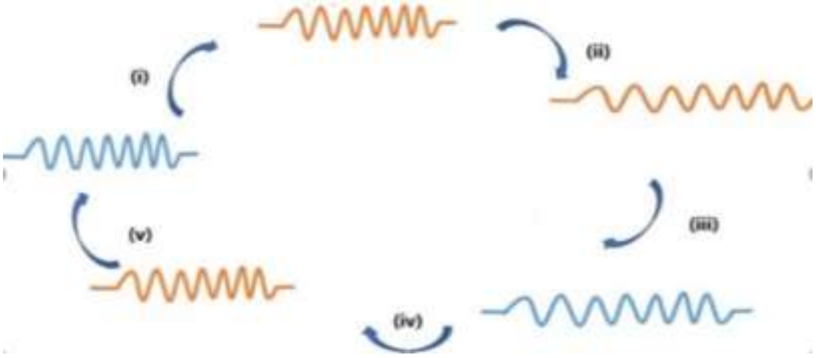

Figure 4. Working of SMA material(spring) (i) heating, (ii) deformation due to stress (iii) cooling in deformed state (iv) stress removal (v) repetition

Temperature-induced crystallographic changes cause the SMAs to exhibit form memory. During these changes, the material transforms from martensite to austenite structure. The alloy takes on a martensitic structure with low stiffness at low temperatures, and external stress can plastically deform it. Reaching above the transition temperature converts it to an austenitic form with high stiffness, recovering the material to its initial undeformed shape. These alloys can be employed as actuators by taking advantage of the contraction of up to 5% achieved when heated from martensite to austenite phases.

Latest developments include the incorporation of SMAs with compliant materials like silicone elastomers to improve object adaptability [39, 40, 41]. SMA microgrippers were created using stiff materials and flexural joints. In these micro-grippers, softness can be improved by using super-elastic SMAs by reducing the thickness of the structure [42].

### *3.1.2. Magnetic Responsive Actuation*

These actuators work by controlling the magnetic field magnitude and direction. They are used in places with high magnetic susceptibility [43]. Magnetic stimulation is appealing due to the ease with which it is possible to regulate the magnetic field's direction and magnitude quickly and precisely and its capacity to permeate most materials. Magnetic particles and fillers are blended with polymers, gels, papers, and fluids so that they could operate on applying magnetic fields externally. When discrete magnetic fillers are inserted into soft materials, a magnetic profile with varying amplitude and direction is generated [44].

### *3.1.3. Photo Responsive Actuation*

This type of actuation can be achieved in the Visible light-driven and the Near Infrared (NIR) light actuator. Because of the potential of long-wavelength NIR light to permeate biomaterials with low losses, NIR has emerged as the most biocompatible way of wireless actuation for biomedical devices. Visible light-driven actuators can actuate in sunlight, saving a lot of excess energy when working in an open or natural environment [44].

### *3.1.4. Electrically responsive actuators (EAPs)*

For this type of actuation, specific kinds of materials are needed which can show deformation whenever there is a fluctuation in electrical conditions like dielectric elastomers, piezoelectric materials, and mechanical servo motors. While hydraulic or pneumatic actuation has been used in many soft robot designs, a lot of work has gone into developing electrically activated soft actuators made of EAPs. Developing electrically actuated soft actuators comprised of electroactive polymers has taken a lot of time. Some of them are even prototyped. Because energy is more easily reserved in electrical form and computation is commonly performed on electronic circuits, actuating soft robotics directly using electrical potential may be more efficient. Piezoelectric, ferroelectric polymers, mechanical or servo motors, ionic EAPs, dielectric EAPs are some examples of EAPs [11].

#### *a. Dielectric Elastomer Actuators (DEA)*

A thin elastomer membrane (thickness 3–500 μm) [45] is sandwiched between two compliant electrodes in a DEA. An electric attraction (known as Maxwekk stress) between the electrodes is created by applying high voltage, resulting in compression of the elastomer membrane and expansion of its area. Soft elastomers having an elastic modulus of 1MPa are used to makes DEAs, as they have a quick reaction time and may create massive actuation strokes.

Furthermore, their electromechanical efficiency is capable of reaching 90%. Multilayer stacking is required when high output forces are demanded due to the long actuation stroke and low generated stress of DEAs, resulting in a more complicated fabrication method. Due to their inherent simplicity, they can be shaped in any configuration. Recent developments and commercial availability of the kV thin-film transistors [46] and miniaturized high voltage components have enabled the designing of more compact systems.

The first demonstration of the usage of DEAs for gripping was having a design known as self-organized dielectric elastomer minimal energy structures (DEMESs) [47]. The main problem in this type of system is to overcome the low generated stress. For this particular problem, other than multilayer stacking, different techniques like incorporating variable stiffness functionality [48], implementation of controllable adhesion [49] are being explored.

### *b. Ionic Polymer Metal Composites (IPMCs)*

IPMCs comprises an expandable membrane of electrolyte polymer (usually thickness of 100-300μm) wedged between two thin metallic layers. Cations and anions in the electrolyte are evenly dispersed when the voltage applied is zero. The concentration of cations increases at the cathode and anions at the anode when voltage is applied, causing non-uniform swelling resulting in the entire structure bending towards the positive side [50]. Thus, the device can be curved bi-directional depending on the applied polarity.

IPMCs have stiffness ranging between 0.60 to 21.0 GPa, influenced by electrode and polymer membrane materials. This actuator technology allows for broad bending strokes for the applied small actuation voltages in the range of 1-5V. Using the electrolyte frequently necessitates the aqueous solution submerging of actuators, but encasement allows for functioning in the dry setting [51]. IPMCs, like DEAs, are capable of self-sensing however their response time is slow [50]. IPMCs have the benefit of being easily made at a millimetre scale. IPMCs have certain disadvantages, like low generated stress and slow actuation response. Exploiting this technology's capacity to work in aquatic conditions could be one way to get it closer to applications.

### *3.1.5. Fluidic Elastomer Actuators (FEAs)*

These actuators are among the oldest and still widely used in soft robotics because of their advantages, such as ease of production, resilience, and low-cost elastomer materials [52]. The fluid applies pressure on the walls of elastic material and provides actuation. FEAs structures often have asymmetric geometry or are made of anisotropic materials, resulting in the chamber's inflation being transformed into bending of the entire actuator. High forces can be generated by FEAs depending on the pressure applied and active surface area.

For FEAs, there are a variety of architectures to choose from. Some of the most prevalent are bellows-like structures, tube-like tentacles, elongated elastomeric chambers with reinforcing layers and fibres etc. The moulding process that makes up the chamber is commonly used in the fabrication of FEAs. Fibres, adhesion, nonprotractile layers textiles and papers, origamis, strain sensors, porous materials and variable stiffness elements can all be incorporated into the actuator using the moulding process (during the molten state of material) [53, 54].

Fibre reinforcement in FEAs resulted in the creation of bioinspired soft hands that can replicate various human movements and manage ordinary things like flasks, pencils, and eyeglasses. Silicone elastomers structurally reinforced with polyaramid fibres are used to achieve properties like self-healing of minor punctures and boosted tear resistance.

Researchers used 3D printing to demonstrate the quick manufacture of FEA-based grippers. Researchers have inserted functional aspects into the grippers' structure to increase their functionality, taking advantage of the diversity given by the moulding process. Resistive strain sensors composed of expandable or pliable electrodes, stretchable optical waveguides, and force sensors employing a piezoresistive fabric component were used to accomplish curvature sensing. Increased holding weight can be achieved by incorporating variable stiffness parts.

Using compressors and external pumps to pressurize fluid for actuation is one possible issue of FEA grippers. These components are frequently big and hefty, compromising the device's portability. Efforts to combine and miniaturize the production of pressurized fluids have yielded hopeful results in the past [55]. Response time can be a problem since, for the full actuation with the required flow rate and given the channel’s fluidic impedance, crossing 1 Hz frequency can be challenging.

## *3.2. Variable Stiffness*

### *3.2.1. Low melting point alloy (LMPA)*

The alloy that undergoes a phase change in response to heat, typically at low temperatures, generally determined by alloy composition, is termed LMPA. Synthetic elastomeric composites have fixed internal structures and defined properties. Unlike natural composites, these materials cannot alter their structure and mechanical properties depending on environmental conditions. For example, the structure of bone changes upon induced mechanical stresses. LMPA inclusions in the elastomeric composites induce a change in stiffness upon phase change. These molten alloys can flow in the pneumatic channels or may be mixed up with the molten elastomer during the fabrication of the structure [56, 57].

A high variation in stiffness can be observed when the alloyed elastomer is heated above the LMPA melting temperature [58, 59]. Soft dielectric materials usually have poor heat conduction as the thermal conductivity is directly proportional to the elastic modulus. This constraint can be overcome with LMPAs added in the elastomer composites resulting in an unrivalled combination having thermal conductivity as high as metals, elastic modulus similar to elastomers and the ability to experience large deformation having strain greater than 600 percent [60].

Further developments include reducing the phase transformation period of LMPAs. Based on geometry and size, melting time can range from 1 to 30 seconds while solidification time can be double. This timing can be an issue when there is a need for quick manipulation [61]; melting time can be reduced by the increment of heat addition while the time to solidify can be reduced using the metal of high thermal conductivity [60] or integration of additional cooling devices like electrocaloric effect based device [61], water circulating system, increase in heat transfer area [62] and fractal channel design [63]. Relative stiffness doesn't change upon scaling the design. However, having a high proportion of PDMS materials and LMPA will increase the power required for the required melting speed. Therefore, the different designs need to be considered (when scaling is done) having low melting time, power requirements and high stiffness [57].

### *3.2.2. Magneto-rheological fluids (MRF) and Electro-rheological fluids (ERF)*

MRF and ERF are the class of suspended particles in fluids that undergo a large reversible variation in the rheological properties (viscosity related properties) when imposed to magnetic and electric fields, respectively [64, 65]. The change in rheological properties when subjected is indicated by flow resistance increment depending on fluid flow direction and constitution. These smart materials are implemented in smart structures, shock absorbers, clutches and brakes [66, 67]. Under an electric field, the particles convert into long fibrous chains aligning in flux lines direction due to molecular dipoles' orientation and dielectric polarization. These chains develop resilience to the deformation of fluid, resulting in increased stiffness of application.

Similarly, MR fluids convert into long chains of ferromagnetic particles aligning in the direction of magnetic flux lines [68, 69]. To initiate viscoelastic behaviour, magnetic field of up to 500mT and an electric field of about 5 kilovolts per mm need to be applied. The response time is relatively short, less than 10 milliseconds and the relative stiffness increases tens of times [70, 71]. ER fluid generally requires low energy as an electric field is proportional to the applied voltage and no steady-state flow of current is needed, while for MR fluid, the magnetic field intensity depends on the electric current. The fluid can be added with elastomeric composites to produce variable stiffness models upon applying the respective actuating fields [72].

### *3.2.3. Granular Jamming*

This is a handy process for constructing changing stiffness media, which is commonly used in robotics applications for gripping complicated and fragile items. Granular jamming is a mechanism that allows granular material to change reversibly from fluidic to solid-state and vice versa. During the fluidic state, granular material can move freely, hence the object feels soft and pliable. Application and removal of vacuum on the bladder containing the grains result in the transition of states [73].

Jamming actuators have a simple structure and use pressure to modulate stiffness. This technique is said to be capable of changing stiffness by nearly 24 times [74]. The stiffness change rate is relatively rapid; for the solidification state, it takes 0.1-1.1s whereas for the fluidic state, it takes 0.1-1seconds [14, 75]. The transition time is typically on the flow rate & pressure differential obtained from the pump and the volume of the granule-filled bladder. When portability is necessary, the pump required to generate a relatively high-pressure differential becomes a limitation. Nonetheless, granular jamming has demonstrated its utilization in mobile manipulators and robots [76, 77].

Once the gripper goes into the solidified state, it is difficult to accommodate object deformation therefore unsuitable for deformable objects. This universal jamming gripper has been employed in some industry setups and has also proved its utility in research applications like assembly tasks, prosthetics, human cooperation and learning algorithm integration [78]. Future granular jamming research could focus on expanding the flexibility of object kinds. Jamming grippers, for example, might be outfitted with adhesive technology to allow them to grasp deformable and flat objects which are difficult as of now. Layer jamming is a technology that uses a variable stiffness method and is dependent on interlayer friction. Because of its low thickness, it has potential future utilization in lightweight fingered grippers with adjustable stiffness [79].

### ***3.3. Variable Adhesion***

Adhesion is the attraction between two surfaces at their common interface, which causes shear stress to be a direct function of the normal pressure generated. Soft gripper having adhesive techniques generate greater grasping forces because of the considerable shear friction force. Simultaneously, the closure force normal to the object's surface is significantly less than the forces in other grasping techniques, allowing the handling of delicate or fragile objects. Low power need, high ratio of shear force to closing force are some of the attributes needed for having a lightweight and easily transportable gripper. Controlled adhesion can primarily be done by electro and gecko adhesion (dry adhesion).

#### ***3.3.1. Electrostatic Adhesion***

The electrostatic force is the attraction force between opposite electric charges. Electro adhesion takes advantage of this nature of attraction by adjusting the electric charges on both sides of the gripper-object common surface [49]. Charge polarization in dielectric models and electrostatic charge induction in the conductive models is an implication of the applied electric field. The electric fields are generated by the interdigitated electrodes with a thin layer of passivation coating. On both smooth and uneven surfaces, electro adhesion has been successful. High electric fields are required for this adhesion method, which necessitates voltages on the order of a few kilovolts current. World technology uses electro-adhesion in different types of rigid and flexible grippers, vertical climbing, water handling etc. [80, 81, 82]. An eight-leaf flexible, electrostatic adhesive gripper has been fabricated and thoroughly discussed in [83].

Electro adhesion is electrically controlled and may be utilized with dielectric objects, and metallic objects with any kind of surfaces in most cases [82]. It eliminates the need for extra actuators to grasp or leave an object. After the voltage is removed, there is a little residual adhesive force. However, residual forces are exceedingly low for dielectric objects and persist barely for some seconds [84, 85, 86]. Using AC voltage instead of DC for conductive objects is a good solution. Electro adhesion performance is also affected by surface conditions for example presence of unwanted materials like dust and moisture will result in a lower holding force. A solution to this problem is in implementing techniques like self-cleaning [87].

#### ***3.3.2. Gecko Adhesion***

Geckos can climb up tilted surfaces using the van der Waals forces to attract surface molecules, generating shear forces. Gecko adhesion was inspired by the surface adhesion developed by microfibres of geckos [88, 89, 90]. The adhesion is done by the microfibers on their bottom foot surface and triggered by pressing them normally to the object surface (preloading) and disengaged by eliminating the preloaded force. Directional shear force during adhesion can also be feasible by adjusting the angle of setal-fibres [91]. Gecko adhesive adheres to both rough and smooth surfaces, although it struggles to stick to low-surface-energy materials [92]. In this form of adhesive technology, self-cleaning is a unique feature [93, 94]. It has also been demonstrated that applying a surface coating on gecko-inspired pillars allows them to stick to damp surfaces.

A new convex object gripping approach that relies almost entirely on shear forces has been discussed in [95]. Also, the gripper uses gecko-inspired-film fibrillar adhesives that conform to the object's curvature. The model has been proposed & validated for grasping a variety of curvatures. Also, inspired by gecko, adhesion microfibres are replicated by angled micropillars made from elastomers with round or flat tips introduced as compliant micromanipulators for pick and place operations [96].

The adaptability of soft grippers with gecko adhesion was demonstrated by their ability to adhere to various objects, among which most were rigid and smooth surfaces. Handling rough-surfaced things and manipulating soft, malleable objects are two examples of potential obstacles. Shape optimizations and microfibres material could be a possible solution for the former. Enhanced adhesion performance on rough surfaces has been achieved by enhancing the bending behaviour of gecko adhesion pillars [97]. Microspines are another promising candidate, as they demonstrated extraordinary grabbing abilities on hard surfaces like concrete and rubble.

## 4. SENSORS

The development of sensors for soft robotic applications has evolved into a research trend over the past few years. This is because of: a) increase in demand for more intelligent systems, b) interests in developing soft robots and other applications that require confirmation to different shapes. Sensors are described as devices that “convert physical quantities such as pressure, temperature, force, acceleration, deformations into electrical signals being input to the control system”. Implanting stretchable sensors on soft grippers would vastly intensify how they can interact with the object and simultaneously obtain information about the manipulated object's characteristics.

Pressure sensors can be used to monitor grasping force. Rubber encapsulated MEMS pressure sensor can be incorporated with a gripper, allowing real-time grasping force monitoring. Force information can be indicated with the help of LED lights, which changes colour when pressure exceeds a predefined threshold [98]. Pressure sensors are mostly based on the capacitive or resistive structures, and these were developed from soft matter and attached to the silicone skin of the palm and fingertips [99] of the robot's hand to obtain the pre touch perception. With the help of these sensors and an algorithm, the robotic hand could determine the suitable closing pattern from the capacitive sensor data [100, 101]. Soft robotic and wearable systems experience large deformation and require sensors to measure this deformation. Graphene materials provide magnificent properties that integrate several flexible and stretchable characteristics into electronic devices. Resistive sensors embedded in the material change its resistance on bending, which is converted into voltage and interpreted by the Arduino. The data obtained from the pressure sensor (Honeywell-ASDX AVX100 PGA A5) is also utilized in computing bending angles corresponding to the pressure. The above data correlates with the actual bending angle observed from the developed vision system for better accuracy and feedback [102]. Highly stretchable strain sensors are conventionally made of carbon black (CB)- filled elastomer composites (up-to 500%) [54]. Recent advances in stretchable electronic materials are discussed in [103, 104] and applications in [105].

Tactile sensing is necessary to have safe contact with surrounding humans and objects. Tactile sensing is done with a permanent magnet embedded in a soft elastomer placed over a hall sensor to compute total force vectors (both shear and normal forces). This sensing is also used for palpation and diagnosis of tissues [106, 107, 108]. Several tactile sensors perform better using micro-electro-mechanical systems (MEMS) technology. Some practical problems during the application of MEMS in systems include endurance, wiring difficulties and corrosion. One of the best alternatives to MEMS is fibre optic sensors which are appealing due to their performance capability and resilience to several environmental disturbances, especially electromagnetic and electrostatic fields. Human skin touch sensors are incorporated into devices like grippers or robot hands to pursue human fingers' equivalent skill and adaptability. Having these on our prototypes or robots will eventually give us a large set of information that can be backtracked for design evolution. These sensors can detect the distributed force using micro-bending of optical fibres and are used for artificial skins [99, 109, 110, 111, 112, 113] and reflective heartbeat sensors based on optical fibres [114].

Depending on the type of work to be carried out, various types of soft actuators are applicable in the medical and surgery field. The actuators in the surgery field need to be precise and provide accurate data. For collecting different kinds of data, the actuators are fitted with proprioception sensors [35] like fibre bragg grating (FBG), stretchable resistance or conductance sensor, environmental perception sensors like flexible optical fibre and interactive perception sensors. The screen-printed sensors were printed on elastomeric substrates and incorporated with soft pneumatic actuators in a single process [115]. With the help of these sensors, the true curvature of an actuator can be known within the sensor hysteresis and creep limits. The key advantages of these sensors are: a) need less time to manufacture b) need a small amount of additional effort in the actuator manufacturing, and c) are made with readily available equipment and materials. Measurement of small fluctuating or variable parameters is vital in any robotic application that includes interaction with the environment because it enables the robot to identify encounters early and respond appropriately. Taking inspiration from the ciliary structure found in nature, a Miniaturized Light force sensor has been developed, designed, and simulated [116].

## 5. CONCLUSION AND FUTURE SCOPE

This paper discusses how the advent of technologies has impacted robot structures. Since performing jobs with delicacy has been demanded for a long time and rigid robots have been unable to fulfil that idea, the soft robots have outdone them in this field. The hyper redundant robots somehow stand on the line with structural strength from the rigid robot’s point of view and abilities to stretch, squeeze and morph from their soft counterparts. The different hyper redundant robots that are developed are a sort of inspiration from nature. To achieve desirable robotic behaviour in real-world situations, an insight of characteristics, interface with control systems and environment of soft materials is also required. Advanced materials are the heart of these types of robots as they play a vital role in deciding the system's speed, force, adhesion, and kinematics. Different materials like silicone elastomer, hydrogels, shape memory alloy, electroactive polymer etc., are used to get the desired deformation of the system. However, the peak of commercializing these specific robots have not reached. So, it becomes important that these potential robots are continuously evolved with upcoming technologies so that they don’t become obsolete. There is a need to look upon the properties of materials like self-healing and room temperature actuation of SMAs. Combining advanced materials and processes definitely increases the system's complexity, but it will undoubtedly be a topic of discussion in the near future if the performance is enhanced. Enhancement of interaction of soft robots with objects can be greatly done with the implementation of stretchable sensors. Ongoingly, research is being done to develop sensors that measure and sense various parameters like pressure, temperature, force, strain, proximity and shear. Some problems may be encountered during the practical application of tactile sensing using MEMS technology and the best alternative to them is fibre optic sensors. These are attractive due to their performance capability and resilience to environmental disruptions. The overall rapid rate of advancements in optical fibre-based sensors suggests a bright future for them. Systems such as soft robots that undergo large deformations require sensors that can withstand these large deformations. Future works include manufacturing graphene films possessing high conductivity, chemically stable in air, good uniformity and the ability to adhere to device substrates. This will enhance the performance and longevity of the resulting devices.

## REFERENCES

[1] I. Fiorello, E. Del Dottore, F. Tramacere, and B. Mazzolai, ‘Taking inspiration from climbing plants: methodologies and benchmarks—a review,’ Bioinspir. Biomim., vol. 15, no. 3, p. 031001, May 2020, doi: 10.1088/1748-3190/ab7416.

[2] 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.

[3] S. Kim, C. Laschi, and B. Trimmer, ‘Soft robotics: a bioinspired evolution in robotics,’ Trends Biotechnol., vol. 31, no. 5, pp. 287–294, May 2013, doi: 10.1016/j.tibtech.2013.03.002.

[4] A. Souhail and P. Vassakosol, ‘Low cost soft robotic grippers for reliable grasping,’ J. Mech. Eng. Res. Dev., vol. 41, no. 4, pp. 88–95, 2018, doi: 10.26480/jmerd.04.2018.88.95.

[5] C. H. Liu and C. H. Chiu, ‘Optimal design of a soft robotic gripper with high mechanical advantage for grasping irregular objects,’ Proc. - IEEE Int. Conf. Robot. Autom., pp. 2846–2851, 2017, doi: 10.1109/ICRA.2017.7989332.

[6] J. Paek, I. Cho, and J. Kim, ‘Microrobotic tentacles with spiral bending capability based on shape-engineered elastomeric microtubes,’ Sci. Rep., vol. 5, no. March, pp. 1–11, 2015, doi: 10.1038/srep10768.

[7] R. V. Martinez et al., ‘Robotic tentacles with three-dimensional mobility based on flexible elastomers,’ Adv. Mater., vol. 25, no. 2, pp. 205–212, 2013, doi: 10.1002/adma.201203002.

[8] Y. Sun et al., ‘Stiffness Customization and Patterning for Property Modulation of Silicone-Based Soft Pneumatic Actuators,’ Soft Robot., vol. 4, no. 3, pp. 251–260, 2017, doi: 10.1089/soro.2016.0047.

[9] M. Calisti et al., ‘An octopus-bioinspired solution to movement and manipulation for soft robots,’ Bioinspiration and Biomimetics, vol. 6, no. 3, 2011, doi: 10.1088/1748-3182/6/3/036002.

[10] M. Cianchetti, M. Calisti, L. Margheri, M. Kuba, and C. Laschi, ‘Bioinspired locomotion and grasping in water: The soft eight-arm OCTOPUS robot,’ Bioinspiration and Biomimetics, vol. 10, no. 3, pp. 1–19, 2015, doi: 10.1088/1748-3190/10/3/035003.

[11] D. Rus and M. T. Tolley, ‘Design, fabrication and control of soft robots,’ Nature, vol. 521, no. 7553, pp. 467–475, 2015, doi: 10.1038/nature14543.

[12] W. Wang, C. Li, M. Cho, and S. H. Ahn, ‘Soft Tendril-Inspired Grippers: Shape Morphing of Programmable Polymer-Paper Bilayer Composites,’ ACS Appl. Mater. Interfaces, vol. 10, no. 12, pp. 10419–10427, 2018, doi: 10.1021/acsami.7b18079.

[13] A. Sadeghi, A. Tonazzini, L. Popova, and B. Mazzolai, ‘Robotic mechanism for soil penetration inspired by plant root,’ Proc. - IEEE Int. Conf. Robot. Autom., pp. 3457–3462, 2013, doi: 10.1109/ICRA.2013.6631060.

[14] H. M. J. and H. L. J.R. amend, E.brown, N.rodernberg, ‘a positive pressure universal gripper based on yhe jamming of granular material,’ IEEE Trans. Robot., vol. 28, no. 2, pp. 341–350, 2012, doi: 10.31812/apd.v0i14.1833.

[15] F. Ongaro et al., ‘Autonomous planning and control of soft untethered grippers in unstructured environments,’ J. Micro-Bio Robot., vol. 12, no. 1–4, pp. 45–52, 2017, doi: 10.1007/s12213-016-0091-1.

[16] Z. Xie et al., ‘Octopus Arm-Inspired Tapered Soft Actuators with Suckers for Improved Grasping,’ Soft Robot., vol. 7, no. 5, pp. 639–648, 2020, doi: 10.1089/soro.2019.0082.

[17] T. Umedachi, V. Vikas, and B. A. Trimmer, ‘Softworms: The design and control of non-pneumatic, 3D-printed, deformable robots,’ Bioinspiration and Biomimetics, vol. 11, no. 2, p. 0, 2016, doi: 10.1088/1748-3190/11/2/025001.

[18] T. Umedachi, M. Shimizu, and Y. Kawahara, ‘Caterpillar-Inspired Crawling Robot Using Both Compression and Bending Deformations,’ IEEE Robot. Autom. Lett., vol. 4, no. 2, pp. 670–676, 2019, doi: 10.1109/LRA.2019.2893438.

[19] C. J. Cai et al., ‘Diversified and Untethered Motion Generation Via Crease Patterning from Magnetically Actuated Caterpillar-Inspired Origami Robot,’ IEEE/ASME Trans. Mechatronics, vol. 26, no. 3, pp. 1678–1688, 2021, doi: 10.1109/TMECH.2020.3028746.

[20] L. Cortese, S. Milanovic, and R. Vidoni, ‘A FEM-Experimental Approach for the Development of a Conceptual Linear Actuator Based on Tendril’s Free Coiling,’ Appl. Bionics Biomech., vol. 2017, 2017, doi: 10.1155/2017/6450949.

[21] R. Vidoni, T. Mimmo, and C. Pandolfi, ‘Tendril-Based Climbing Plants to Model, Simulate and Create Bio-Inspired Robotic Systems,’ J. Bionic Eng., vol. 12, no. 2, pp. 250–262, 2015, doi: 10.1016/S1672-6529(14)60117-7.

[22] M. Wooten, C. Frazelle, I. D. Walker, A. Kapadia, and J. H. Lee, ‘Exploration and inspection with vine-inspired continuum robots,’ Proc. - IEEE Int. Conf. Robot. Autom., pp. 5526–5533, 2018, doi: 10.1109/ICRA.2018.8461132.

[23] B. A. Jones and I. D. Walker, ‘Kinematics for multisection continuum robots,’ IEEE Trans. Robot., vol. 22, no. 1, pp. 43–55, 2006, doi: 10.1109/TRO.2005.861458.

[24] B. A. Jones, W. McMahan, and I. D. Walker, ‘Practical kinematics for real-time implementation of continuum robots,’ Proc. - IEEE Int. Conf. Robot. Autom., vol. 2006, no. 6, pp. 1840–1847, 2006, doi: 10.1109/ROBOT.2006.1641974.

[25] T. McMillen and A. Goriely, ‘Tendril perversion in intrinsically curved rods,’ J. Nonlinear Sci., vol. 12, no. 3, pp. 241–281, 2002, doi: 10.1007/s00332-002-0493-1.

[26] J. Fraś, M. Maciaś, F. Czubaczyński, P. Salek, and J. Glówka, ‘Soft flexible gripper design, characterization and application,’ Adv. Intell. Syst. Comput., vol. 543, pp. 368–377, 2017, doi: 10.1007/978-3-319-48923-0_40.

[27] P. Polygerinos, Z. Wang, K. C. Galloway, R. J. Wood, and C. J. Walsh, ‘Soft robotic glove for combined assistance and at-home rehabilitation,’ Rob. Auton. Syst., vol. 73, pp. 135–143, 2015, doi: 10.1016/j.robot.2014.08.014.

[28] S. Ueki et al., ‘Development of a hand-assist robot with multi-degrees-of-freedom for rehabilitation therapy,’ IEEE/ASME Trans. Mechatronics, vol. 17, no. 1, pp. 136–146, 2012, doi: 10.1109/TMECH.2010.2090353.

[29] J. Zhao, X. Zheng, M. Zheng, A. J. Shih, and K. Xu, ‘An endoscopic continuum testbed for finalizing system characteristics of a surgical robot for NOTES procedures,’ 2013 IEEE/ASME Int. Conf. Adv. Intell. Mechatronics Mechatronics Hum. Wellbeing, AIM 2013, pp. 63–70, 2013, doi: 10.1109/AIM.2013.6584069.

[30] A. Bajo, R. E. Goldman, L. Wang, D. Fowler, and N. Simaan, ‘Integration and preliminary evaluation of an Insertable Robotic Effectors Platform for Single Port Access Surgery,’ Proc. - IEEE Int. Conf. Robot. Autom., pp. 3381–3387, 2012, doi: 10.1109/ICRA.2012.6224986.

[31] D. C. R. and H. C. J.Burgner-kahrs, ‘Continuum robots for medical application: a survey,’ IEEE tansactions Robot., vol. 31, no. 6, pp. 1261–1280, 2015.

[32] P. Taylor, D. Trivedi, C. D. Rahn, W. M. Kier, and I. D. Walker, ‘Applied Bionics and Biomechanics Soft robotics : Biological inspiration , state of the art , and future research,’ no. October 2014, pp. 37–41, doi: 10.1080/11762320802557865.

[33] G. J. Monkman, ‘Controllable Retention,’ vol. 5, no. July 1994, pp. 567–575, 2015.

[34] C. W. K.Otsuka, shape memory materials. 1998.

[35] J. Zhu et al., ‘Intelligent Soft Surgical Robots for Next-Generation Minimally Invasive Surgery,’ Adv. Intell. Syst., vol. 3, no. 5, p. 2100011, 2021, doi: 10.1002/aisy.202100011.

[36] M. D. Hager, S. Bode, C. Weber, and U. S. Schubert, ‘Shape memory polymers: Past, present and future developments,’ Prog. Polym. Sci., vol. 49–50, pp. 3–33, 2015, doi: 10.1016/j.progpolymsci.2015.04.002.

[37] L. Sun et al., ‘Stimulus-responsive shape memory materials: A review,’ Mater. Des., vol. 33, no. 1, pp. 577–640, 2012, doi: 10.1016/j.matdes.2011.04.065.

[38] H. Meng and G. Li, ‘A review of stimuli-responsive shape memory polymer composites,’ Polymer (Guildf)., vol. 54, no. 9, pp. 2199–2221, 2013, doi: 10.1016/j.polymer.2013.02.023.

[39] W. Wang, H. Rodrigue, H. Il Kim, M. W. Han, and S. H. Ahn, ‘Soft composite hinge actuator and application to compliant robotic gripper,’ Compos. Part B Eng., vol. 98, pp. 397–405, 2016, doi: 10.1016/j.compositesb.2016.05.030.

[40] H. Rodrigue, W. Wang, D. R. Kim, and S. H. Ahn, ‘Curved shape memory alloy-based soft actuators and application to soft gripper,’ Compos. Struct., vol. 176, pp. 398–406, 2017, doi: 10.1016/j.compstruct.2017.05.056.

[41] Y. Zhou, H. Jin, C. Liu, E. Dong, M. Xu, and J. Yang, ‘A novel biomimetic jellyfish robot based on a soft and smart modular structure (SMS),’ 2016 IEEE Int. Conf. Robot. Biomimetics, ROBIO 2016, pp. 708–713, 2016, doi: 10.1109/ROBIO.2016.7866406.

[42] C. C. Lan, C. M. Lin, and C. H. Fan, ‘A self-sensing microgripper module with wide handling ranges,’ IEEE/ASME Trans. Mechatronics, vol. 16, no. 1, pp. 141–150, Feb. 2011, doi: 10.1109/TMECH.2009.2037495.

[43] S. Kaluvan, C. Y. Park, and S. B. Choi, ‘Bio-inspired device: A novel smart MR spring featuring tendril structure,’ Smart Mater. Struct., vol. 25, no. 1, p. 01LT01, 2015, doi: 10.1088/0964-1726/25/1/01LT01.

[44] N. El-Atab et al., ‘Soft Actuators for Soft Robotic Applications: A Review,’ Adv. Intell. Syst., vol. 2, no. 10, p. 2000128, 2020, doi: 10.1002/aisy.202000128.

[45] A. Poulin, S. Rosset, and H. R. Shea, ‘Printing low-voltage dielectric elastomer actuators,’ Appl. Phys. Lett., vol. 107, no. 24, 2015, doi: 10.1063/1.4937735.

[46] A. Marette, A. Poulin, N. Besse, S. Rosset, D. Briand, and H. Shea, ‘Flexible Zinc–Tin Oxide Thin Film Transistors Operating at 1 kV for Integrated Switching of Dielectric Elastomer Actuators Arrays,’ Adv. Mater., vol. 29, no. 30, pp. 1–6, 2017, doi: 10.1002/adma.201700880.

[47] G. Kofod, M. Paajanen, and S. Bauer, ‘Self-organized minimum-energy structures for dielectric elastomer actuators,’ Appl. Phys. A Mater. Sci. Process., vol. 85, no. 2, pp. 141–143, 2006, doi: 10.1007/s00339-006-3680-3.

[48] H. Imamura, K. Kadooka, and M. Taya, ‘A variable stiffness dielectric elastomer actuator based on electrostatic chucking,’ Soft Matter, vol. 13, no. 18, pp. 3440–3448, 2017, doi: 10.1039/c7sm00546f.

[49] J. Shintake, S. Rosset, B. Schubert, D. Floreano, and H. Shea, ‘Versatile Soft Grippers with Intrinsic Electroadhesion Based on Multifunctional Polymer Actuators,’ Adv. Mater., vol. 28, no. 2, pp. 231–238, 2016, doi: 10.1002/adma.201504264.

[50] S. Nemat-Nasser and Y. Wu, ‘Comparative experimental study of ionic polymer-metal composites with different backbone ionomers and in various cation forms,’ J. Appl. Phys., vol. 93, no. 9, pp. 5255–5267, 2003, doi: 10.1063/1.1563300.

[51] J. Barramba, J. Silva, and P. J. Costa Branco, ‘Evaluation of dielectric gel coating for encapsulation of ionic polymer-metal composite (IPMC) actuators,’ Sensors Actuators, A Phys., vol. 140, no. 2, pp. 232–238, 2007, doi: 10.1016/j.sna.2007.06.035.

[52] B. Gorissen, D. Reynaerts, S. Konishi, K. Yoshida, J. W. Kim, and M. De Volder, ‘Elastic Inflatable Actuators for Soft Robotic Applications,’ Adv. Mater., vol. 29, no. 43, pp. 1–14, 2017, doi: 10.1002/adma.201604977.

[53] F. Connolly, P. Polygerinos, C. J. Walsh, and K. Bertoldi, ‘Mechanical programming of soft actuators by varying fiber angle,’ Soft Robot., vol. 2, no. 1, pp. 26–32, 2015, doi: 10.1089/soro.2015.0001.

[54] F. Connolly, C. J. Walsh, and K. Bertoldi, ‘Automatic design of fiber-reinforced soft actuators for trajectory matching,’ Proc. Natl. Acad. Sci. U. S. A., vol. 114, no. 1, pp. 51–56, 2017, doi: 10.1073/pnas.1615140114.

[55] A. Yamaguchi, K. Takemura, S. Yokota, and K. Edamura, ‘Ii. Electro-Conjugate Fluid,’ 2011.

[56] A. C. Siegel, D. A. Bruzewicz, D. B. Weibel, and G. M. Whitesides, ‘Microsolidics: Fabrication of three-dimensional metallic microstructures in poly(dimethylsiloxane),’ Adv. Mater., vol. 19, no. 5, pp. 727–733, 2007, doi: 10.1002/adma.200601787.

[57] B. E. Schubert and D. Floreano, ‘Variable stiffness material based on rigid low-melting-point-alloy microstructures embedded in soft poly(dimethylsiloxane) (PDMS),’ RSC Adv., vol. 3, no. 46, pp. 24671–24679, 2013, doi: 10.1039/c3ra44412k.

[58] A. Tonazzini, S. Mintchev, B. Schubert, B. Mazzolai, J. Shintake, and D. Floreano, ‘Variable Stiffness Fiber with Self-Healing Capability,’ Adv. Mater., vol. 28, no. 46, pp. 10142–10148, 2016, doi: 10.1002/adma.201602580.

[59] W. Shan, T. Lu, and C. Majidi, ‘Soft-matter composites with electrically tunable elastic rigidity,’ Smart Mater. Struct., vol. 22, no. 8, 2013, doi: 10.1088/0964-1726/22/8/085005.

[60] S. H. Jeong et al., ‘Mechanically Stretchable and Electrically Insulating Thermal Elastomer Composite by Liquid Alloy Droplet Embedment,’ Sci. Rep., vol. 5, no. December, pp. 1–10, 2015, doi: 10.1038/srep18257.

[61] J. Shintake, B. Schubert, S. Rosset, H. Shea, and D. Floreano, ‘Variable stiffness actuator for soft robotics using dielectric elastomer and low-melting-point alloy,’ IEEE Int. Conf. Intell. Robot. Syst., vol. 2015-Decem, pp. 1097–1102, 2015, doi: 10.1109/IROS.2015.7353507.

[62] S. Launay, A. G. Fedorov, Y. Joshi, A. Cao, and P. M. Ajayan, ‘Hybrid micro-nano structured thermal interfaces for pool boiling heat transfer enhancement,’ Microelectronics J., vol. 37, no. 11, pp. 1158–1164, 2006, doi: 10.1016/j.mejo.2005.07.016.

[63] Y. Chen and P. Cheng, ‘Heat transfer and pressure drop in fractal tree-like microchannel nets,’ Int. J. Heat Mass Transf., vol. 45, no. 13, pp. 2643–2648, 2002, doi: 10.1016/S0017-9310(02)00013-3.

[64] J. W. Sohn, G. W. Kim, and S. B. Choi, ‘A state-of-the-art review on robots and medical devices using smart fluids and shape memory alloys,’ Appl. Sci., vol. 8, no. 10, 2018, doi: 10.3390/app8101928.

[65] T. Hao, ‘Electrorheological Fluids.’

[66] J. P. Coulter, K. D. Weiss, and J. D. Carlson, ‘Engineering applications of electrorheological materials,’ J. Intell. Mater. Syst. Struct., vol. 4, no. 2, pp. 248–259, 1993, doi: 10.1177/1045389X9300400215.

[67] J. D. Carlson, D. M. Catanzarite, and K. A. St. Clair, ‘COMMERCIAL MAGNETO-RHEOLOGICAL FLUID DEVICES,’ Int. J. Mod. Phys. B, vol. 10, no. 23n24, pp. 2857–2865, Oct. 1996, doi: 10.1142/S0217979296001306.

[68] P. Sheng and W. Wen, ‘Electrorheological fluids: Mechanisms, dynamics, and microfluidics applications,’ Annu. Rev. Fluid Mech., vol. 44, pp. 143–174, 2011, doi: 10.1146/annurev-fluid-120710-101024.

[69] J. De Vicente, D. J. Klingenberg, and R. Hidalgo-Alvarez, ‘Magnetorheological fluids: A review,’ Soft Matter, vol. 7, no. 8, pp. 3701–3710, 2011, doi: 10.1039/c0sm01221a.

[70] S. Sun et al., ‘A Compact Variable Stiffness and Damping Shock Absorber for Vehicle Suspension,’ IEEE/ASME Trans. Mechatronics, vol. 20, no. 5, pp. 2621–2629, 2015, doi: 10.1109/TMECH.2015.2406319.

[71] M. Eshaghi, R. Sedaghati, and S. Rakheja, ‘Dynamic characteristics and control of magnetorheological/electrorheological sandwich structures: A state-of-the-art review,’ J. Intell. Mater. Syst. Struct., vol. 27, no. 15, pp. 2003–2037, 2016, doi: 10.1177/1045389X15620041.

[72] M. Kallio, T. Lindroos, S. Aalto, E. Järvinen, T. Kärnä, and T. Meinander, ‘Dynamic compression testing of a tunable spring element consisting of a magnetorheological elastomer,’ Smart Mater. Struct., vol. 16, no. 2, pp. 506–514, 2007, doi: 10.1088/0964-1726/16/2/032.

[73] H. M. Jaeger, ‘Celebrating Soft Matter’s 10th Anniversary: Toward jamming by design,’ Soft Matter, vol. 11, no. 1, pp. 12–27, 2015, doi: 10.1039/c4sm01923g.

[74] A. Jiang et al., ‘Robotic Granular Jamming: Does the Membrane Matter?,’ Soft Robot., vol. 1, no. 3, pp. 192–201, 2014, doi: 10.1089/soro.2014.0002.

[75] J. Amend, N. Cheng, S. Fakhouri, and B. Culley, ‘Soft Robotics Commercialization: Jamming Grippers from Research to Product,’ Soft Robot., vol. 3, no. 4, pp. 213–222, 2016, doi: 10.1089/soro.2016.0021.

[76] E. Steltz, A. Mozeika, J. Rembisz, N. Corson, and H. M. Jaeger, ‘Jamming as an enabling technology for soft robotics,’ Electroact. Polym. Actuators Devices 2010, vol. 7642, p. 764225, 2010, doi: 10.1117/12.853182.

[77] S. G. Fitzgerald, G. W. Delaney, and D. Howard, ‘A review of jamming actuation in soft robotics,’ Actuators, vol. 9, no. 4, pp. 1–31, 2020, doi: 10.3390/act9040104.

[78] S. Reitelshofer, C. Ramer, D. Graf, F. Matern, and J. Franke, ‘Combining a collaborative robot and a lightweight Jamming-Gripper to realize an intuitively to use and flexible co-worker,’ 2014 IEEE/SICE Int. Symp. Syst. Integr. SII 2014, no. 0, pp. 1–5, 2014, doi: 10.1109/SII.2014.7028001.

[79] Y. J. Kim, S. Cheng, S. Kim, and K. Iagnemma, ‘A novel layer jamming mechanism with tunable stiffness capability for minimally invasive surgery,’ IEEE Trans. Robot., vol. 29, no. 4, pp. 1031–1042, 2013, doi: 10.1109/TRO.2013.2256313.

[80] K. Asano, F. Hatakeyama, and K. Yatsuzuka, ‘Fundamental study of an electrostatic chuck for silicon wafer handling,’ IEEE Trans. Ind. Appl., vol. 38, no. 3, pp. 840–845, 2002, doi: 10.1109/TIA.2002.1003438.

[81] H. Wang, A. Yamamoto, and T. Higuchi, ‘A crawler climbing robot integrating electroadhesion and electrostatic actuation,’ Int. J. Adv. Robot. Syst., vol. 11, pp. 1–11, 2014, doi: 10.5772/59118.

[82] H. Prahlad, R. Pelrine, S. Stanford, J. Marlow, and R. Kornbluh, ‘Electroadhesive robots - Wall climbing robots enabled by a novel, robust, and electrically controllable adhesion technology,’ Proc. - IEEE Int. Conf. Robot. Autom., pp. 3028–3033, 2008, doi: 10.1109/ROBOT.2008.4543670.

[83] E. W. Schaler, D. Ruffatto, P. Glick, V. White, and A. Parness, ‘An electrostatic gripper for flexible objects,’ IEEE Int. Conf. Intell. Robot. Syst., vol. 2017-Septe, pp. 1172–1179, 2017, doi: 10.1109/IROS.2017.8202289.

[84] P. M. Taylor, G. J. Monkman, and G. J. F. Farnworth, ‘Principles of electroadhesion in clothing robotics,’ Int. J. Cloth. Sci. Technol., vol. 1, no. 3, pp. 14–20, 1989, doi: 10.1108/eb002951.

[85] J. Singh, ‘Electro-Adhesive Gripper Component Selection for Pick and Place of Commonly Used Materials,’ 2019.

[86] K. Yatsuzuka, F. Hatakeyama, K. Asano, and S. Aonuma, ‘Fundamental characteristics of electrostatic wafer chuck with insulating sealant,’ IEEE Trans. Ind. Appl., vol. 36, no. 2, pp. 510–516, 2000, doi: 10.1109/28.833768.

[87] Y. Lu, S. Sathasivam, J. Song, C. R. Crick, C. J. Carmalt, I. P. Parkin, ‘Robust self-cleaning surfaces that function when exposed to either air or oil,’ Science (80-. )., vol. 347, no. 6226, 2015.

[88] L. F. Boesel, C. Cremer, E. Arzt, and A. Del Campo, ‘Gecko-inspired surfaces: A path to strong and reversible dry adhesives,’ Adv. Mater., vol. 22, no. 19, pp. 2125–2137, 2010, doi: 10.1002/adma.200903200.

[89] M. Zhou, N. Pesika, H. Zeng, Y. Tian, and J. Israelachvili, ‘Recent advances in gecko adhesion and friction mechanisms and development of gecko-inspired dry adhesive surfaces,’ Friction, vol. 1, no. 2, pp. 114–129, 2013, doi: 10.1007/s40544-013-0011-5.

[90] Y. Li, J. Krahn, and C. Menon, ‘Bioinspired Dry Adhesive Materials and Their Application in Robotics: A Review,’ J. Bionic Eng., vol. 13, no. 2, pp. 181–199, 2016, doi: 10.1016/S1672-6529(16)60293-7.

[91] D. S. and M. R. C. S. Kim, M. Spenko, S. Trujillo, B. Heyneman, ‘Smooth Vertical Surface Climbing With Directional Adhesion,’ IEEE Trans. Robot., vol. 24, no. 1, pp. 65–74, 2008.

[92] K. Autumn and A. M. Peattie, ‘Mechanisms of adhesion in geckos,’ Integr. Comp. Biol., vol. 42, no. 6, pp. 1081–1090, 2002, doi: 10.1093/icb/42.6.1081.

[93] J. Lee and R. S. Fearing, ‘Contact self-cleaning of synthetic gecko adhesive from polymer microfibers,’ Langmuir, vol. 24, no. 19, pp. 10587–10591, 2008, doi: 10.1021/la8021485.

[94] Y. Mengüç, M. Röhrig, U. Abusomwan, H. Hölscher, and M. Sitti, ‘Staying sticky: Contact self-cleaning of gecko-inspired adhesives,’ J. R. Soc. Interface, vol. 11, no. 94, 2014, doi: 10.1098/rsif.2013.1205.

[95] E. W. Hawkes, D. L. Christensen, A. K. Han, H. Jiang, and M. R. Cutkosky, ‘Grasping without squeezing: Shear adhesion gripper with fibrillar thin film,’ Proc. - IEEE Int. Conf. Robot. Autom., vol. 2015-June, no. June, pp. 2305–2312, 2015, doi: 10.1109/ICRA.2015.7139505.

[96] Y. Mengüç, S. Y. Yang, S. Kim, J. A. Rogers, and M. Sitti, ‘Gecko-inspired controllable adhesive structures applied to micromanipulation,’ Adv. Funct. Mater., vol. 22, no. 6, pp. 1246–1254, 2012, doi: 10.1002/adfm.201101783.

[97] H. Hu et al., ‘Discretely Supported Dry Adhesive Film Inspired by Biological Bending Behavior for Enhanced Performance on a Rough Surface,’ ACS Appl. Mater. Interfaces, vol. 9, no. 8, pp. 7752–7760, 2017, doi: 10.1021/acsami.6b14951.

[98] J. Gafford et al., ‘Shape deposition manufacturing of a soft, atraumatic, deployable surgical grasper,’ J. Med. Devices, Trans. ASME, vol. 8, no. 3, 2014, doi: 10.1115/1.4027048.

[99] H. Huang, J. Lin, L. Wu, Z. Wen, and M. Dong, ‘Trigger-based dexterous operation with multimodal sensors for soft robotic hand,’ Appl. Sci., vol. 11, no. 19, 2021, doi: 10.3390/app11198978.

[100] M. Tavakoli et al., ‘Autonomous Selection of Closing Posture of a Robotic Hand Through Embodied Soft Matter Capacitive Sensors,’ IEEE Sens. J., vol. 17, no. 17, pp. 5669–5677, 2017, doi: 10.1109/JSEN.2017.2726348.

[101] H. Vandeparre, D. Watson, and S. P. Lacour, ‘Extremely robust and conformable capacitive pressure sensors based on flexible polyurethane foams and stretchable metallization,’ Appl. Phys. Lett., vol. 103, no. 20, 2013, doi: 10.1063/1.4832416.

[102] K. Elgeneidy, N. Lohse, and M. Jackson, ‘Bending angle prediction and control of soft pneumatic actuators with embedded flex sensors – A data-driven approach,’ Mechatronics, vol. 50, no. October, pp. 234–247, 2018, doi: 10.1016/j.mechatronics.2017.10.005.

[103] D. McCoul, W. Hu, M. Gao, V. Mehta, and Q. Pei, ‘Recent Advances in Stretchable and Transparent Electronic Materials,’ Adv. Electron. Mater., vol. 2, no. 5, pp. 1–51, 2016, doi: 10.1002/aelm.201500407.

[104] H. Jang, Y. J. Park, X. Chen, T. Das, M. S. Kim, and J. H. Ahn, ‘Graphene-Based Flexible and Stretchable Electronics,’ Adv. Mater., vol. 28, no. 22, pp. 4184–4202, 2016, doi: 10.1002/adma.201504245.

[105] M. Amjadi, K. U. Kyung, I. Park, and M. Sitti, 'Stretchable, Skin-Mountable, and Wearable Strain Sensors and Their Potential Applications: A Review,' Adv. Funct. Mater., vol. 26, no. 11, pp. 1678–1698, 2016, doi: 10.1002/adfm.201504755.

[106] D. S. Chathuranga, Z. Wang, Y. Noh, T. Nanayakkara, and S. Hirai, 'Magnetic and Mechanical Modeling of a Soft Three-Axis Force Sensor,' IEEE Sens. J., vol. 16, no. 13, pp. 5298–5307, 2016, doi: 10.1109/JSEN.2016.2550605.

[107] T. Paulino et al., 'Low-cost 3-axis soft tactile sensors for the human-friendly robot Vizzy,' Proc. - IEEE Int. Conf. Robot. Autom., pp. 966–971, 2017, doi: 10.1109/ICRA.2017.7989118.

[108] Institute of Electrical and Electronics Engineers., 'INES 2013 : proceedings : IEEE 17th International Conference on Intelligent Engineering Systems : June 19-21, 2013, Costa Rica.,' p. 364, 2013.

[109] J. S. Heo, K. Y. Kim, and J. J. Lee, 'Development of a distributed force detectable artificial skin using microbending optical fiber sensors,' J. Intell. Mater. Syst. Struct., vol. 20, no. 17, pp. 2029–2036, 2009, doi: 10.1177/1045389X09348256.

[110] S. Bauer, S. Bauer-Gogonea, I. Graz, M. Kaltenbrunner, C. Keplinger, and R. Schwödiauer, '25th anniversary article: A soft future: From robots and sensor skin to energy harvesters,' Adv. Mater., vol. 26, no. 1, pp. 149–162, 2014, doi: 10.1002/adma.201303349.

[111] M. L. Hammock, A. Chortos, B. C. K. Tee, J. B. H. Tok, and Z. Bao, '25th anniversary article: The evolution of electronic skin (E-Skin): A brief history, design considerations, and recent progress,' Adv. Mater., vol. 25, no. 42, pp. 5997–6038, 2013, doi: 10.1002/adma.201302240.

[112] V. A. Ho, H. Yamashita, Z. Wang, S. Hirai, and K. Shibuya, 'Wrin'Tac: Tactile Sensing System with Wrinkle's Morphological Change,' IEEE Trans. Ind. Informatics, vol. 13, no. 5, pp. 2496–2506, 2017, doi: 10.1109/TII.2017.2718660.

[113] R. M. R. F. Spano, A. Dabrowska, B.M. Quandt, L. Boesel, Empa, A. Massaro, and A. Lay-Ekuakille, 'IEEE NANO 2015 15th International Conference on Nanotechnology : July 27-30, 2015, Rome,' Flex. touch sensors based nanocomposites Embed. Polym. Opt. fibers Artif. Ski. Appl., pp. 27–30, 2015.

[114] B. M. Quandt et al., 'Body-monitoring with photonic textiles: A reflective heartbeat sensor based on polymer optical fibres,' J. R. Soc. Interface, vol. 14, no. 128, 2017, doi: 10.1098/rsif.2017.0060.

[115] A. Koivikko, E. S. Raei, M. Mosallaei, M. Mäntysalo, and V. Sariola, 'Screen-printed curvature sensors for soft robots,' IEEE Sens. J., vol. 18, no. 1, pp. 223–230, 2018, doi: 10.1109/JSEN.2017.2765745.

[116] P. Ribeiro et al., 'A Miniaturized Force Sensor Based on Hair-Like Flexible Magnetized Cylinders Deposited over a Giant Magnetoresistive Sensor,' IEEE Trans. Magn., vol. 53, no. 11, pp. 1–5, 2017, doi: 10.1109/TMAG.2017.2714625.

## Biographies

**Dr. Shubhashis Sanyal** received Master of Technology in Machine Design from IIT Roorkee, philosophy of doctorate degree in Mechanical Engineering at Rani Durgavati Vishwavidyalaya, Jabalpur (M.P.). He has worked at many administrative positions, including Dean Faculty Welfare, Dean R&C etc., and currently working as a professor in Department of Mechanical Engineering at National Institute of Technology, Raipur. His area of interest includes Synthesis of Mechanisms, Stress Analysis, Stress Concentration Factor, Biomechanics, Comfort Analysis.

**Dr. Anuj Kumar Shukla** received Master of Technology in Engineering Mechanics from IIT Delhi, philosophy of doctorate degree in Mechanical Engineering at IIT Delhi. He is currently working as assistant professor in Department of Mechanical Engineering at National Institute of Technology, Raipur. His area of interest includes Computational Fluid Dynamics (CFD), Convective Heat Transfer, Thermal Engineering, Turbulence Modelling, Simulation, RANS, LES, Filtration and Clean Air.

**Hrishi Sharad Pinjan** currently 4th year student in Department of Mechanical Engineering at National Institute of Technology, Raipur pursuing bachelor of technology degree. His area of interest includes Design, Soft Robotics, Automation,

**Piyush Tailor** currently 4th year student in Department of Mechanical Engineering at National Institute of Technology, Raipur pursuing bachelor of technology degree. His area of interest includes Soft Robotics, Automation, Design.

**Pyla Pavan Kumar** currently 4th year student in Department of Mechanical Engineering at National Institute of Technology, Raipur pursuing bachelor of technology degree. His area of interest includes Soft Robotics, Design, Automation

**Surjeet Kumar Bhargav** currently 4th year student in Department of Mechanical Engineering at National Institute of Technology, Raipur pursuing bachelor of technology degree. His area of interest includes Design, Soft Robotics, Automation,

**Suman Saurav** currently 4th year student in Department of Mechanical Engineering at National Institute of Technology, Raipur pursuing bachelor of technology degree. His area of interest includes Design, Soft Robotics, Automation,