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SOFT ROBOTICS (M SPENKO, SECTION EDITOR)

Actuation Technologies for Soft Robot Grippers and Manipulators: A Review

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Abstract

Purpose of Review The new paradigm of soft robotics has been widely developed in the international robotics community. These robots being soft can be used in applications where delicate yet effective interaction is necessary. Soft grippers and manipulators are important, and their actuation is a fundamental area of study. The main purpose of this work is to provide readers with fast references to actuation technologies for soft robotic grippers in relation to their intended application.

Recent Findings The authors have surveyed recent findings on actuation technologies for soft grippers. They presented six major kinds of technologies which are either used independently for actuation or in combination, e.g., pneumatic actuation combined with electro-adhesion, for certain applications.

Summary A review on the latest actuation technologies for soft grippers and manipulators is presented. Readers will get a guide on the various methods of technology utilization based on the application.

Keywords Soft robotics · Soft actuation technologies · Soft grippers · Soft manipulators

Introduction

Soft robotics has introduced the world to a new class of robots that has helped the researchers in finding solutions to the problems that rigid systems are not able to cope with. Owing to their soft nature, they are safe to interact with human beings as eradicating the danger of harm during operation. Their ease of adjusting with the environment, picking and placing of delicate objects without damaging them, and flexibility to operate in complicated environments, as compared to their rigid counterparts, are some other benefits they offer. This novel field is demonstrating these advantages in a number of applications such as biomedical and industrial ones, especially through the development of soft manipulators and grippers. In this work, soft manipulator refers to continuum arm that can morph its shape to perform different operations, while soft gripper refers to end-effector used to handle, hold, or grasp objects through the use of fingers or suction cups. It can also be attached to the manipulator for high degree of maneuverability.

In [1], the authors provided an overview for the readers about existing soft robotic grippers, the materials used in their fabrication, and their different designs. A classification of soft grippers based on configuration, actuation, application, size, and stiffness was presented by Samadikhoshkho et al. in their work [2]. Hughes et al. reviewed the state of the art for soft manipulators in their paper, focusing on the material and fabrication processes, actuation technologies, sensing methods, and structures. They mentioned that further research is needed to develop systems with increased speeds and precision that can expand the applications of manipulators in the fields of agriculture and industry [3].

Different actuation technologies have been developed and are widely in use. Soft grippers employ actuators that make them adapt to objects of various shapes, material, and stiffness [4]. In this paper, focus has been laid on the different actuation technologies and how the main physical principle has been exploited by each research group for targeted applications.

This article is part of the Topical Collection on *Soft Robotics*

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Starting from pneumatic actuation, the paper progresses by discussing vacuum, cable-driven, and shape memory alloy actuation. Also included are other actuation types based on electroactive polymers and electro-adhesion followed by discussion and conclusion. The main operating mechanism associated to the performances of the developed devices and the target applications have been also collected and presented in different tables related to each actuation technology, to provide the reader a clear overview of the design choices in the development of soft grippers and manipulators. The performance hexagon has also been made part of the paper (Fig. 1) so that the reader can understand and compare the performances of the discussed actuation technologies.

Pneumatic Actuation

Pneumatic actuation (Table 1) is the most popular type of actuation used in soft robots for gripping various objects by using positive pressures. It is based on pressurizing purposively designed soft chambers so as to have pre-set deformations, like bending (Fig. 2). Researchers have utilized this type of actuation for different targeted applications. Lee et al. used pneumatic networks (PneuNets) type of soft bending actuators comprising of air chambers and constraint layer for actuating soft grippers composed of finger-like parts. The conformable grasping with low contact pressure and high lifting force was attained by the use of stiffness patterning by arranging nodes of different stiffness in a specific manner in the constraint layer of the actuator [5•], which guides an asymmetric deformation. Nguyen et al. made use of pneumatic actuation for controlling a tri-stable robotic finger by employing bi-stable buckling springs which can maintain two stable states depending on the energy input. They took into account three stable states of grasping: open, pinch, and wrap by employing two bi-stable springs of soft and stiff nature in the finger [6]. Kim et al. replaced the compressor by an origami pump driven by tendons to control the bending angle of a soft robotic finger. The operating mechanism comprised of bending and releasing of fingers through pulling and releasing of tendons [7].

Ariyanto et al. managed the inflation and deflation of their three-fingered gripper by the use of external mini air compressor connected to a solenoid valve which regulated the entry and exit of air into the gripper [8]. The problem of low actuation speed and fingertip force of soft pneumatic actuators (SPAs) was addressed by Park et al. They developed a hybrid PneuNet actuator by integrating rigid structures into the soft part of the gripper. The round edge shape between rigid and soft material was responsible for high fingertip force, while the fast PneuNet with a high number of chambers and channels enhanced the actuation speed of the gripper [9]. Another work by Meng et al. made use of a hybrid approach which combined the characteristics of tendon-driven grippers and the SPAs. The quick release mechanism of soft fingers was controlled by tendons which resulted in grasping objects at high actuation speeds. The pneumatic actuation was used for inflating the three-fingered soft gripper and the soft pneumatic telescopic palm [10]. The telescopic palm structure has multiple segments; the third placed inside the second and second placed inside the first just like the structure of the telescope.

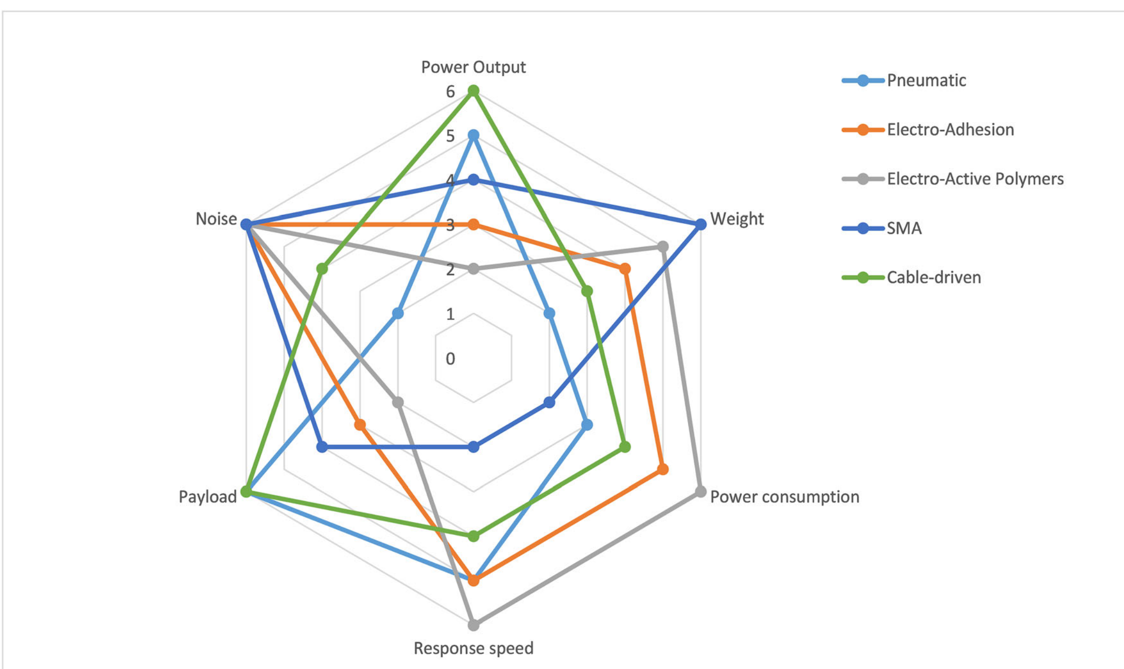

Fig. 1 Comparative analysis in arbitrary scale from 0 (poor performance) to 6 (good performance)

Table 1 Applications, operating mechanisms, and performance parameters of cited papers related to pneumatic actuation

Authors	Applications	Operating mechanism	Performance parameters
Lee et al. (2020) [1]	Pick and place of random objects	1. Low contact forces for handling delicate objects were desired 2. Constraint layer with stiffness patterns was attached to the actuation chambers	Under identical actuating pressure: • Lifting force of customized soft grippers = 3 × the lifting force of non-patterned soft grippers • Maximum contact force of former = 2/3 × force of latter
Nguyen et al. (2020) [2]	Pinch and wrap grasps of different objects; twisting of bulb, holding of water balloon, lifting of flat objects, e.g., paper	1. Pressure variation from low to high changed the posture patterns of the gripper (pinch, wrap, and opening posture)	• Pull and torque tests were conducted for the tri-stable and control grippers • With the 20-mm diameter test objects, the tri-stable fingers outperformed the control by 312% on average across all three geometries in both tests • For 20-, 40-, 60-mm-sized objects, tri-stable gripper improved performance by: 186% in z axis pull, 375% in x axis pull, 129% in roll torque, and 342% in yaw torque
Kim et al. (2020) [3]	Grasping of different objects like ring-shaped snack, cup, table tennis ball, balloon	1. For achieving the bending, the motor pulled the tendons through rotation. Tendons in turn compressed the origami pump which released the air into the actuator 2. Posterior part of the finger expanded when the volume of the actuator increased resulting in an increased bending angle	• Hysteresis characteristics were observed during operation of pneumatic actuator • Experimentally determined values for the actuator: • Natural frequency ~3 Hz • Estimated elastic modulus =43.28 kPa • Estimated moment of inertia =1.80×10^{-9} kgm^2
Ariyanto et al. (2019) [4]	Grasping of both soft and hard materials	1. For inflation, the first valve (out of two) closed while the compressed air entered into the gripper through the second valve, and the reverse was true for the deflation process	• Highest bending angle= 270° at 30 kPa • Under positive pressure, the gripper can stably grasp object of mass < 500 g
Park et al. (2019) [5•]	Pick and place of different objects, e.g., tape, bowl	1. Compact actuation system comprised of two pumps, pressure sensors and the solenoid valve for the inflation of hybrid gripper	Using the hybrid design vs. conventional actuators: • Fingertip force increased 1.5–2 times • Actuation speed increased 1.3 times
Meng et al. (2020) [6]	Grasping of objects like box, cup, plastic bottle, baseball, football, can	1. Telescopic palm, upon increasing the pressure, inflated in order to protect the onboard sensors and also provided better conformability to the grasped objects	• Gripper weight = 657g • Finger bending ~270 degrees Grasping test was performed for 6 different objects • Max time = 0.7s was recorded to grasp plastic bottle weighing 46.31g, size = 200 mm × 100 mm × 55 mm
Hisatomi et al. (2019) [7]	Forcep manipulator driven by soft pneumatic actuator; used in surgical robots	1. Soft actuator comprised of silicone rubber reinforced by two springs: one for controlling radial expansion of actuator and other for enhancing the bending stiffness 2. By entering air at different pressures into the four chambers inside the actuator, different bending angles of the forceps manipulator were achieved	For forceps manipulator: • Length = 340 mm • Weight = 23 g • Maximum bending angle= 53°
Luo et al. (2019) [8]	Grasping of various objects under dry as well as wet and slippery conditions	1. Control system comprised of microcontroller, pump, and valve. Opening and closing of pump and valve for the supply of air to the soft fingers were controlled by the microcontroller which read the pressure values provided by the pressure sensor	• Experiments showed that the gripper based on nano-fiber film array outperformed the one without film in grasping fruits underwater in terms of weight: • Weight lifted by gripper without film underwater: Peach = ~115 g, banana = ~103 g, melon= ~95 g • Weight lifted by gripper with film underwater: Peach = ~135 g, banana= ~123 g, melon = ~103 g
Venter et al. (2017) [9]	Handling and manipulation of delicate produce in horticultural applications	1. Each out of four soft gripper fingers contained a separate air chamber. Upon applying positive pressure, the fingers formed a closed grip, and the reverse held true for an opening posture	• Not discussed
Falco et al. (2017) [10]	pneumatically actuated manipulator with a functional tip; targeted for surgical applications	1. Inside the modules, four semi-cylindrical pneumatic chambers were kept which were actuated through external air valves through silicone pipes 2. Two different modes of module bending occurred when one or two chambers were actuated, while elongation of the module was produced when all three chambers were actuated with equal pressure	Motion tests demonstrated that: • Manipulator can elongate up to 53% of the initial length • Bend up to 248 and 85° in case of 1-chamber and 2-chamber bending, respectively Stiffness tests demonstrated that: • When the granular jamming was activated by 0.1 MPa vacuum pressure, the stiffness of the manipulator increased up to 80%
Tawk et al. (2019) [11]	Grasped different objects like screwdriver, banana, cup, soap block	1. Fin-Ray inspired structure was added to the design to enhance the gripping ability of the soft gripper and get highly conformable grasp	• Maximum experimental tip blocked force generated by the actuator was 4.26 N

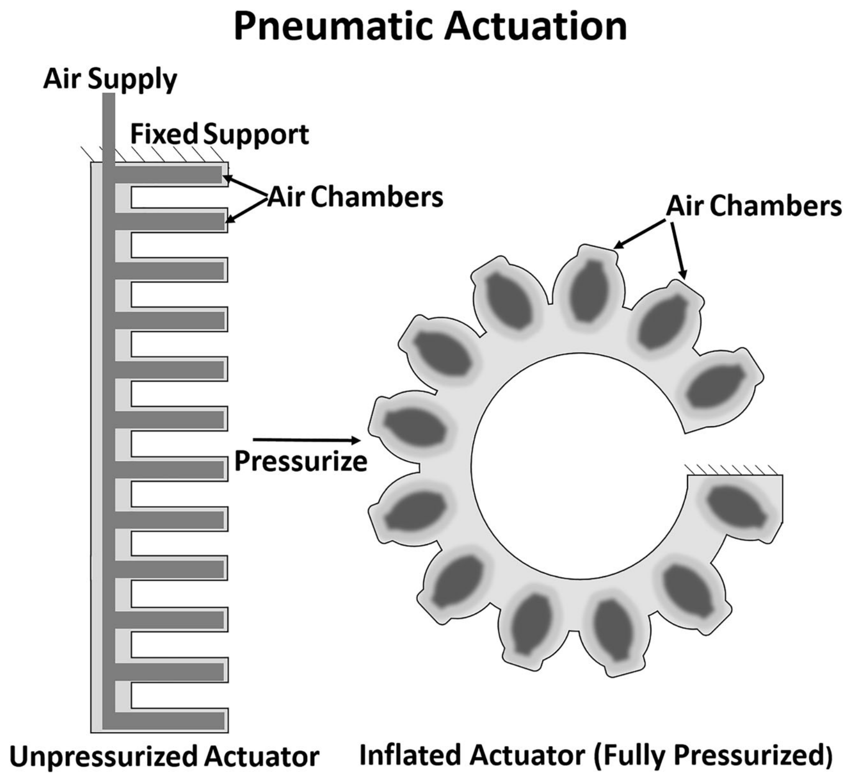

Fig. 2 Working principle of pneumatic actuation

Compared to the conventional forceps manipulators driven by wires, Hisatomi et al. developed their manipulator based on SPAs in the bending joints, thus avoiding the friction caused due to wires [11].

For grasping objects in wet and slippery conditions, Luo et al. modified the surface of pneumatic actuators by making use of a biomimetic nano-fiber array film (polydimethylsiloxane). For the actuation purpose, they used the pneumatic drive. The degree of fingers' bending depended on their internal air pressure [12•]. Venter et al. developed a soft gripper for picking and handling delicate fruits, for attaining lower contact pressure and equal distribution of force around the picked fruit [13]. Soft manipulators and grippers driven by pneumatic actuators are also popular in minimally invasive surgery. De Falco et al. introduced an octopus-inspired mini-manipulator equipped with a gripper at its tip. The manipulator was able to bend in all directions along with the elongation. It comprised of three modules connected with each other. Each module was a soft cylinder made of silicone rubber. The opening and closing of gripper depended on the inflation and deflation of air inside the pneumatic cylinder [14]. Tawk et al. enhanced the capabilities of a pneumatically actuated soft gripper by adding structures inspired by Fin-Ray effect (fish fins bend in S-shape when they are subjected to external load — this way a wrap is formed around the load/object to be grasped resulting in adaptive grasping) such that objects of different shapes, stiffness, and weight could be efficiently grasped [15].

Vacuum Actuation

Vacuum actuation (Table 2) has also been employed in different grippers. Conceptually, it is the same as pneumatic actuation, but here, the negative pressure instead of positive pressure is utilized for actuation (Fig. 3). Jain et al. worked on an actively controlled soft reconfigurable palm with three fingers and retractable nails. The fingertip as well as the finger nail orientations was changed by controlling the vacuum input of the soft palm. Moreover, the nail grasping forces were also enhanced by changing the vacuum input to the active palm [16]. This system had an added feature of pinch grasping of mini and flat objects. 3D-printed linear soft vacuum actuators (LSOVA) were manufactured by Tawk et al. LSOVA possessed multiple advantages including ease of manufacturing, scalability, and increased actuations speeds. The authors successfully tested these actuators in a number of soft systems like crawling robot inside a transparent plastic channel, soft manipulator, soft artificial muscle, as well as soft gripper and prosthetic fingers [17••].

Vacuum bending actuators (VBA) for continuum manipulators were designed and fabricated by Katugampala et al. They tested a single VBA as well as a bimorph actuator comprising of two VBAs to get multi-plane motions. The authors successfully developed a continuum manipulator consisting of three VBAs [18]. The characteristics of both positive and negative pressurization were utilized by Fatahillah et al. who proposed a positive and negative pressure (PNP) actuator. The

Table 2 Applications, operating mechanisms, and performance parameters of cited papers related to vacuum actuation

Authors	Applications	Operating mechanism	Performance parameters
Jain et al. (2020) [12•]	Grasping of common items	1. Using a vacuum pump, the palm and fingers were actuated through four programmable vacuum regulators	• Retracted nails can exert normal grasping forces up to 1.8 N • Enable grasping of objects up to 200 µm thick from flat surfaces
Tawk et al. (2019) [13]	LSOVAs have been used in different applications like soft artificial muscles, soft prosthetic fingers, and soft manipulators for pick and place tasks	1. LSOVA are easy to manufacture, produce large forces, and are scalable	• Experiments showed that LSOVA have high bandwidth of ~6.49 Hz, high output force ~27 N, and long lifetime~21,500 cycles
Katugampala et al.(2019) [14]	Loads were lifted by the manipulator	1. Silicone skeleton was capsuled inside a polyethylene film to form actuator 2. By vacuuming the film cavity, different bending motions of actuators were achieved	• Single vacuum bending actuator of 132 mm length was capable of lifting a maximum load of 204 g and achieving 59 mm displacement and 26° bending angle while lifting 90 g at 10 kPa • 47-g bimorph actuator generated 169 g force in isometric testing
Fatahillah et al. (2020) [15]	Gripping of large objects as well as pinch grasping	1. Benefits of both positive and negative pressures (PNP) were used 2. Simultaneous pressurization and vacuuming of the respective actuators resulted in larger bending force 3. Large bending force at low bending angles were achieved with PNP actuation while high bending angles were obtained with negative pressures only	• Actuator blocked force = 150 N at a combined positive pressure of 60 kPa and negative pressure of 60 kPa • Actuator was implemented in a soft robotic gripper capable of lifting objects up to 4 kg and a soft pinching gripper capable of holding a notebook of 1.85 kg
Bamotra et al. (2018) [16]	Gripping of different objects	1. Authors utilized a central vacuum pump to control suction of multiple holes at the bottom of gripper surface 2. This provided an active grasp control in lifting objects with a large surface area with ease and enhanced grasp stability	• Gripper could lift 100 times its own weight with great ease • Could withstand a maximum force of 40 N

bending of the actuator was achieved by pressurizing one pneumatic actuator while vacuuming the other [19••]. Bamotra et al. fabricated and tested a suction gripper that only utilized a single central vacuum pump to control suction of multiple holes at the bottom of the gripper surface. This suction gripper was capable of lifting payload 100 times its own weight, exhibiting powerful suction capability of the gripper [20].

Cable-Driven Actuation

Another immensely used actuation mechanism in soft robotic grippers and manipulators is the cable-driven actuation (Table 3). It works by controlling the motion of the soft body by retracting the cables that are embedded in the structure and anchored at some specific points (Fig. 4). Although it is flexible and responsive in action, the design of its setup is a challenging task due to placement of motors, pulleys, force sensors, and encoders. Xiang et al. used a two sectioned continuum arm driven by eight cables, each section containing four cables. The soft gripper attached at the end of the arm was also cable-driven in order to perform different picking operations [21]. Yan et al. also used cable-driven actuation for actuating the modules of their manipulator. In their design of soft gripper, they used three modules for gripping of objects. By combing modules in series through connectors, manipulators of different length could be designed. The cables passed through the modules for introducing bending for grasping [22]. For grasping two objects at a time just by pulling a single cable, Honji et al. designed a soft gripper consisting of thin and thick parts; thin parts acted as bending joints, while the thick parts served as the links. The pulling pattern of the cable decided the shape of the gripper for grasping objects [23]. The actuators of a gripper were made smarter by Chen et al. who integrated the soft triboelectric nanogenerators (TENGs) into the cable-driven actuator. TENGs use triboelectric effect to convert small mechanical deformations to electrical signals. Two different types of TENGs were used: one was responsible for measuring contact pressure upon grasping and the other one for detecting bending. A three-fingered gripper design was proposed in this study [24].

Another three-fingered semisoft gripper inspired by origami design was developed by Lee et al. They used an under-

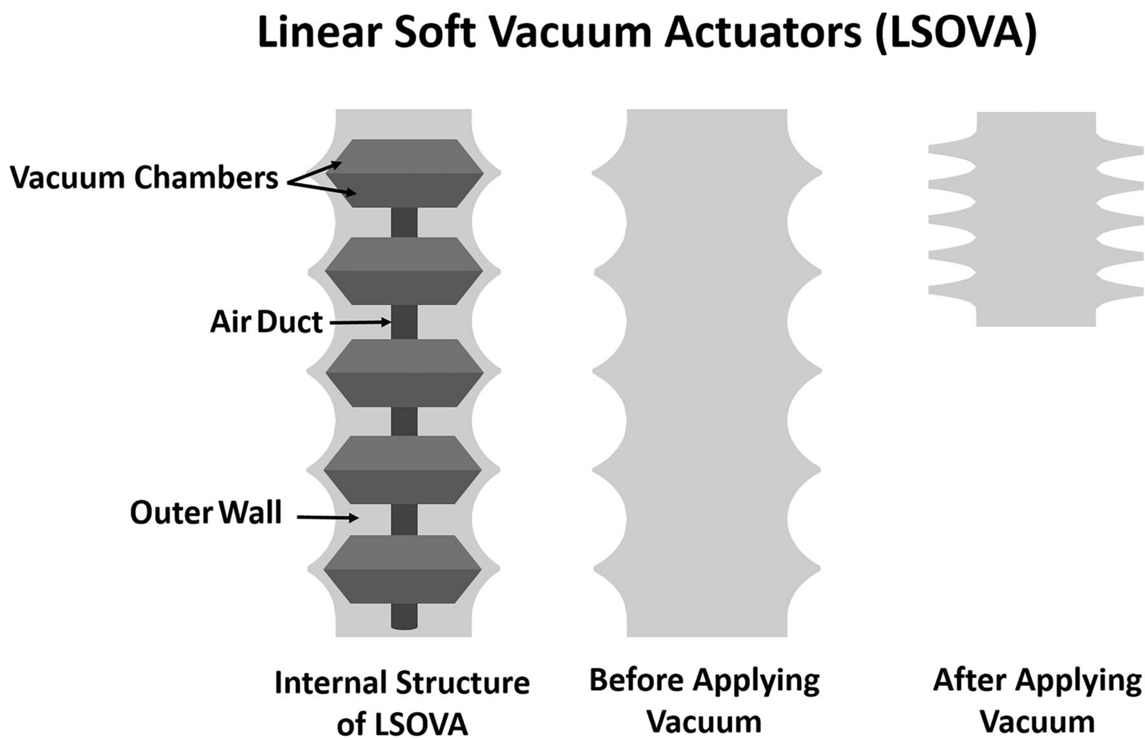

Fig. 3 Working principle of vacuum actuation

actuated system for driving the actuators where one single motor was connected to three cables, each cable passing through a single finger [25]. In contrast to this under-actuated gripper, Chen et al. developed a gripper with three fingers, each actuated by a separate motor. The gripper was designed through the topology optimization method, a performance enhancement technique that removes excessive material from the subject under special conditions using mathematical methods [26]. Cable-driven actuation was employed in a different manner by Jiang et al. They developed a cylindrical manipulator comprising of three sections, each section made up of a different material. They aimed to explore different motion capabilities of the manipulator through the use of multi-materials in a single structure. By pulling the cables that passed through each section, the bending of manipulator was controlled [27].

To make surgical tasks easier and to improve the accuracy of surgical procedures, Wang et al. developed a cable-driven soft robotic manipulator for cardiac ablation surgery on the beating heart. The manipulator was made up of silicone rubber with no electric wires and rigid structures inside, making it completely safe for the human body. The control of the soft manipulator was made through the propulsion plant (responsible for forward, backward, and rotatory motion) and the cables (responsible for controlling end and middle section direction). The manipulator could be pulled out of the body in any particular situation by simply losing the cables [28]. Zhang et al. gave more controllability and flexibility to the surgeon during surgery by dividing the manipulator into two parts, each part driven by four cables. Thanks to two divided parts of the manipulator, the surgeon can decide the cables of which part to be strained, depending on the internal cavity. Different shapes of the manipulator were achieved by pulling different cables. Experiments showed that this soft manipulator was capable of reaching almost all regions of heart [29].

Roels et al. developed a multi-material tendon-driven soft gripper which could recover any structural damages/cuts during its operation. The two materials that were used had different mechanical properties with one thing in common; both were self-healing Diels–Alder polymers. These kinds of polymers involve reversible covalent bonds that form and break through heat-cool cycle which in turn assist in the healing process. The gripper comprising of four fingers opened and closed by pull and release mechanism of tendons and was capable of handling and gripping objects of various shape and size [30].

Shape Memory Alloy Actuation

Shape memory alloys (SMA) (Table 4) have also been used in soft grippers for actuation purposes owing to a number of merits including low noise, high force to weight ratio, small size [31], and the ease of their usage (Fig. 5). Yin et al. designed a gripper comprising of two SMA wire actuated soft fingers coated with sensing skin. The soft gripper switched between open and closed states due to Joule heating. This design helped in passively holding objects as the grippers

Table 3 Applications, operating mechanisms, and performance parameters of cited papers related to cable-driven actuation

Authors	Applications	Operating mechanism	Performance parameters
Xiang et al. (2019) [17••]	System was tested for grasping of various objects	1. Continuum arm comprised of two sections. In Section I, four cables emerged from the top and extended till the end of the arm, while in Section II, four cables began from the middle of the arm and extended till the end 2. Coupling among the two sections was responsible for producing bending in the arm	• Motion control of the manipulator was tested with a payload of 200 g • Manipulator's ability to transport the objects to different sites was validated through cable-driven control system
Yan et al. (2019) [18]	Gripping of objects like egg, bulb, tape, ruler	1. Authors developed three modules for the gripper 2. Each module, having cables passing through it, was reinforced by a spring in the center for improving stiffness and motion stability of the gripper	• Maximum bending angle of module = 180°, error within 2.5° • Total bending angle of manipulator was more than270°, error within 5° • Gripper equipped with 3 modules could grasp objects of different shapes, stiffness, and weights ranging from 1 g to 0.43 kg
Honji et al. (2020) [19••]	Soft gripper that can grasp and manipulate unknown objects dexterously has been proposed	1. When the cable was pulled, the gripper started to open from its initial closed state 2. Upon further pulling the cable, the gripper gradually closed the first grasping point and then the other one for grasping two objects at a single time 3. Upon completely pulling the cable, the gripper closed completely	• Paper focused on the mathematical models of the cable-driven soft silicone gripper • No performance parameters were discussed
Chen et al. (2020) [20]	For picking different kinds of objects	1. Upon receiving pressure or bending values, an electric signal was produced by the TENGs which was used for monitoring the states of the soft actuator. This electric energy could also be harvested for powering other electronics 2. Cable that drove the actuator had its one end connected to a mini DC motor, while the other end was fixed to the tip of the finger 3. Actuator bending was achieved by pulling cables	• Maximum weight that can be grasped = ~500g • Actively generated signals enable the gripper: i. To perceive different actions during grasping ii. To be aware of object dropping and any further contact of the object
Lee et al. (2020) [21]	Gripper was tested for gripping 36 different objects	1. Three fingers of the gripper were tied and actuated at a single time by the motor resulting in opening and closing of the gripper 2. Cables in each finger were routed in zigzag manner in order to induce bending in the actuator	• Among the 36 objects employed, the gripper could successfully grasp 28 objects reliably (3/3 success rate) and 31 objects at least two out of three trials Bending angle = θ, pulling force = F, pulling distance = d • θ = 36° F = 2.05 N d = 40 mm, θ = 68° F = 2.24 N d = 70 mm • θ = 126° F = 2.44 N d = 90 mm, θ = 180° F = 2.76 N d = 100 mm
Chen et al. (2018) [22]	Gripper handled a wide range of objects	1. Ends of the cable in each actuator were tied to the tip of the finger and the roller mounted on the servo motor. Also the cables were partially embedded inside the fingers in order to avoid collision with the grasped objects	• Gripper could handle objects up to 1 kg • Maximum blocking force = 5.7 N
Jiang et al. (2016) [23]	Application not yet explored (in paper till 2016)	1. Three independent cables placed symmetrically passed through the three sections of manipulator 2. By pulling each cable with a different displacement, the manipulator bent to a 3D curve	• From the force vs displacement plot for the three manipulators, the slopes k_k(N.mm$^{2)}$ and intercepts b_k(N) were: $k_1 = 220.77$, $b_1 = -0.0668$, $k_2 = 221.70$, $b_2 = -0.1142$, $k_3 = 227.56$, $b_3 = 0.0097$ • Bending stiffness of three materials 27 A, 40 A, and 50 A were found as: k_b(27A) = 500.97N.mm^2, k_b(40A) = 635.20N.mm^2, k_b(50A) = 862.32 N.mm^2
Wang et al. (2017) [24]	For cardiothoracic endoscopic surgery	1. Cables passed in the longitudinal direction throughout the manipulator 2. Propulsion plant was added to give a better motion performance 3. Through the cables and the propulsion plant, the soft manipulator was completely controlled	• Ablation performance was found to be satisfactory after using the manipulator • No numerical performance parameters were discussed
Zhang et al. (2015) [25]	Application: soft surgical robot	1. Manipulator was divided into two parts; each part driven by four cables 2. By straining the cables, different shapes/patterns of manipulators were achieved	• Two-part manipulator was controlled better than one-part • Had the ability to reach almost every regions of the heart • No numerical performance parameters were discussed
Roels et al. (2019) [26]	Grasp and pick up soft objects of various shapes and sizes	1. The bending of actuators was obtained by pulling single tendon cable going in and out of each finger and into the next one	• Maximum perpendicular force at fingertip = 0.4 N

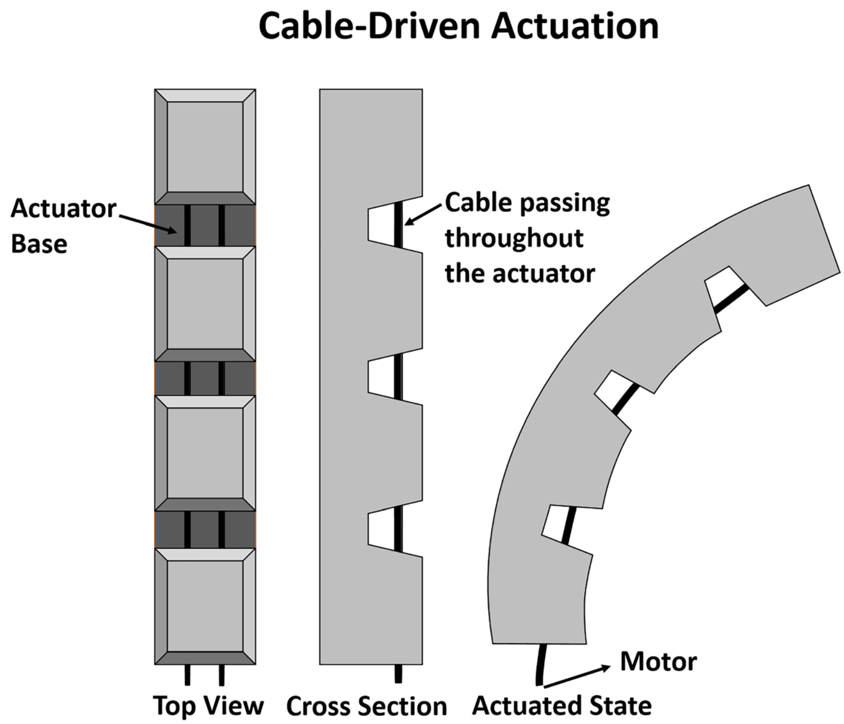

Fig. 4 Working principle of cable-driven actuation

remained in closed position in the absence of power [32]. Hellebrekers et al. also developed a SMA actuated soft gripper. They integrated sensors into the soft elastomeric body of the gripper which were responsible for sensing temperature, pressure, orientation, and proximity. The gripper was designed to hold objects passively through minimizing activation time such that the energy required for operation is conserved [33]. Another work of Liu et al. combined the variable stiffness property of paraffin with the shape memory effects of SMA wires. They developed a soft gripper consisting of three fingers. Each finger had two joints whose stiffness could be changed. The SMA wire passed through the fingers [31].

Besides having only two conditions of on and off through SMAs, Hadi et al. developed a module which could achieve any desired setpoint by using a proper control strategy. In other words, any configuration of the module was possible. By heating the SMA springs individually or together, a differential actuating system was obtained [34]. SMA springs also find their application in biomimetic systems. Golgouneh et al. developed a 2-DoF SMA actuated robotic arm which mimicked the real-time arm movements of the user. The current supply in the SMA springs was controlled by a controller which in turn controlled the arm bending [35]. Yin et al. used three different kinds of SMA wires in their two-fingered soft robotic gripper for multiple purposes. Upon heating the wires, SMA-1 wire changed its modulus, and SMA-2 wire changed its length, while SMA-3 wire showed good elasticity [36]. Obaji et al. developed a three-fingered gripper. In each finger, three SMA springs were embedded inside the silicone elastomer. Two out of them were placed in a way that upon receiving electric current, they bent in a U-shape resulting in bending of finger with a greater force. The direction of third spring was fixed in a way that it did not assist the bending but helped in attaining a stable grasp upon activation [37].

Electroactive Polymer Actuation

Electroactive polymers (EAPs) (Table 5) make use of elastomeric materials that can be actuated upon electrical stimulation on two side electrodes that tend to attract and produce large deformations (Fig. 6). Xu et al. got inspiration from the Venus flytrap to develop their soft gripper based on this actuation technology. They designed a two-leaf structure that could create opposite axial elongation to open and close the gripper. They employed dielectric elastomer (DE) as reconfigurable matter so that it can change its shape and properties. Upon applying voltage, DE exhibits high actuation pressure, short response times, and high expansion efficiencies [38]. Wang et al. also developed their Venus flytrap-inspired gripper to handle objects up to 15 g ranging from strawberries to plastic cups. Their gripper was multilayered made of dielectric minimum energy structures (DEMES) which is a subclass of DE actuators [39]. Hwang et al. made use of the benefits of both electro-adhesion and electroactive polymers for the design and development of their soft gripper. Specifically, the dielectric polymer was used to enhance the grasping force of the gripper by expanding in areal directions [40].

Table 4 Applications, operating mechanisms, and performance parameters of cited papers related to SMA actuation

Authors	Applications	Operating mechanism	Performance parameters
Yin et al. (2020) [27]	System can grasp, transport, and sort items, detect, classify, and locate objects within its scanning workspace	1. SMA actuation was integrated with sensing skin 2. Due to Joule heating, the soft actuator switched between open and closed states; open when heated and closed when power was removed	• Using a time-of-flight distance sensor, the system calculated the length, width, height, and center of mass of an object within a 60 mm × 25 mm workspace • In the scanning state, the sampling rate of the sensor skin was~ 7Hz • One complete scan of the workspace was obtained in 67 s • Time required for the SMA springs to activate and deactivate was 5 s • Execution of single unperturbed run of the finite state machine from initialization to the placement of the object in sorted location in 103 s
Hellebrekers et al. (2018) [28]	Gripping of different objects	1. Sensorized skin could sense temperature, pressure, orientation, and proximity	• Maximum blocking force value = ~0.6 N • Local temperature of the gripper increased to ~440C due to the close proximity to the SMA springs
Liu et al. (2020) [29]	Gripping of different objects	1. Upon heating the SMA, the wire contracted resulting in the bending of fingers at low stiffness 2. Upon cooling the paraffin present inside the joints, the stiffness of the joints increased resulting in high grasping force even if SMA was deactivated	• 10 × increase in maximum grasping force of the gripper by using variable stiffness joints • Time of changing the state of the finger from high stiffness to low stiffness was ~70 s, and the time of the reverse process was ~380 s • Stiffness of the finger are 0.24 N/mm at high stiffness and 0.01 N/mm at low stiffness, respectively, resulting in 18-fold stiffness increase
Hadi et al. (2016) [30]	Application planned for medical purposes (due to bio-adaptability of SMA)	1. Three SMA springs were mounted in 120° around a base spring, all springs passing through the module 2. Heating SMA springs individually or together resulted in a differential actuating system	• SMAs usually provides only two points (on and off) in the work space of the system • Through the control strategy of this work, any desired set point is achievable
Golgouneh et al. (2020) [31]	Used for actuation of robotic arm that mimicked a wearable sleeve (for rehabilitation purpose)	1. Two SMA springs controlled the robotic arm movement 2. Two IMUs were also attached to the arm for obtaining different measurements. The arm bent due to SMA actuation	• Weight of robotic arm = 59 g with a wide controllable range of motion of 119° for the first joint, 123° for the second joint • Steady-state errors of 2.7° and 2.1° for the first and the second joints lead to average RMSE of 11.2 mm for end-effector displacement
Yin et al. (2017) [32]	Gripping of different objects	1. Four SMA-1 wires were used to vary the stiffness of the fingers for enhancing the grasping ability 2. SMA-2 wire was used for actuation, while SMA-3 wire was used for restoring the fingers' posture after every unloading	• Grasping ability of the soft robot gripper increased with the growth of its stiffness by at least 40%
Obaji et al. (2013) [33]	Gripping objects of complex shapes	1. Three SMA springs were embedded inside the silicone elastomer 2. Two SMA springs upon heating formed a U-shape for grasping while the third enabled stable grasp	• Experiments proved that SMAs are a good replacement of actuators • No numerical performance parameters have been presented

Variable stiffness dielectric elastomer actuator (VSDEA) was used to develop a soft gripper able to hold objects up to 11 g by Shintake et al. The DE actuator in this case was introduced in the structure to achieve bending actuation during the grasping, while a low melting point alloy (LMPA) was employed to introduce variable stiffness by switching between hard and soft states through Joule heating. Through the combination of fine bending actuation and variable stiffness, the gripper performed efficiently with a good response time [41]. Zhou et al. also used DEA for fabricating their soft gripper. For constructing the frame of the gripper, they directly used FDM, 3D printing technique, over the DEA membrane. This did not require any kind of adhesives between the DEA and the elastic frame. The authors developed three different actuators. The most optimized design produced a maximum change in tip angle of about 128° with the maximum blocked force of 25 mN [42].

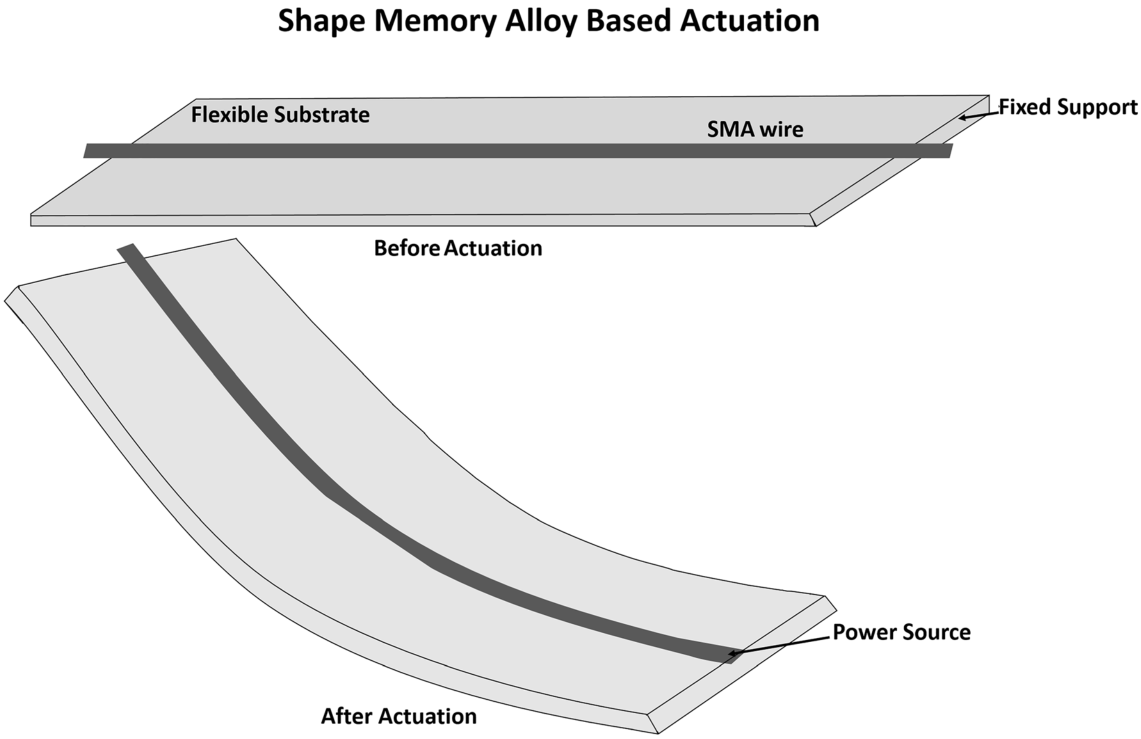

Fig. 5 Working principle of shape memory alloy actuation

Electro-adhesive Actuation

Electro-adhesion (EA) (Table 6) is a further actuation technology that finds application in soft grippers. The principle behind this actuation is that upon applying voltage to the electrodes embedding the dielectric material, an electric field is built which in turn energizes the substrate due to electric induction (Fig. 7). Due to the presence of opposite charge on the substrate and the electro-adhesive pads, the attractive forces help in developing a tight grip. Guo et al. made use of EA actuation as well as DEA

Table 5 Applications, operating mechanisms, and performance parameters of cited papers related to electroactive polymer actuation

Authors	Applications	Operating mechanism	Performance parameters
Xu et al. (2017) [34]	Test was made to grip ping-pong ball	1. Leaves of the gripper opened upon the application of voltage and returned to the original position after removing voltage	• Closing speed of the gripper = 0.25 s • Maximum opening range of 32° upon applying voltage of 5 kV
Wang et al. (2019) [35]	Grasped objects of various sizes and weights	1. Gripper comprised of two bi-stable leaves. Voltage was applied to shift from one minimum energy state to the other one through which the opening and closing actions of the gripper were performed	• Gripper closed upon application of voltage in 0.179 s, and the same time was recorded for its opening action
Hwang et al. (2020) [36]	Objects of various shapes weighing till 625 g can be gripped	1. By stacking single layers of 250 μm DE actuator, multilayered DE actuator was fabricated	• Gripper of 6.2 g mass could lift and move objects of various shapes weighing up to 625 g
Shintake et al. (2015) [37]	Gripper weighing 2 g can hold objects up to 11 g	1. Pre-stretched DEA was attached to the low melting point alloy (LMPA) for the fabrication of the gripper 2. LMPA was responsible for introducing variable stiffness in the gripper through Joule heating	• Controllable actuation angle and the blocked force up to 23.7° and 2.4 mN in the soft state and 0.6° and 2.1 mN in the rigid state • Compared to an actuator without LMPA, VSDEA exhibits ~90 times higher rigidity • Gripper of~2 g (active parts) grasped 11-g object
Zhou et al. (2019) [38]	Gripped a 2 g polyfoam cube	1. FDM was used directly over the DEA membrane for constructing the frame of the gripper. Any kind of adhesives between the DEA and the elastic frame were not required	• The most optimized actuators out of three designs produced a maximum change in tip angle of ~128° with the maximum blocked force of 25 mN

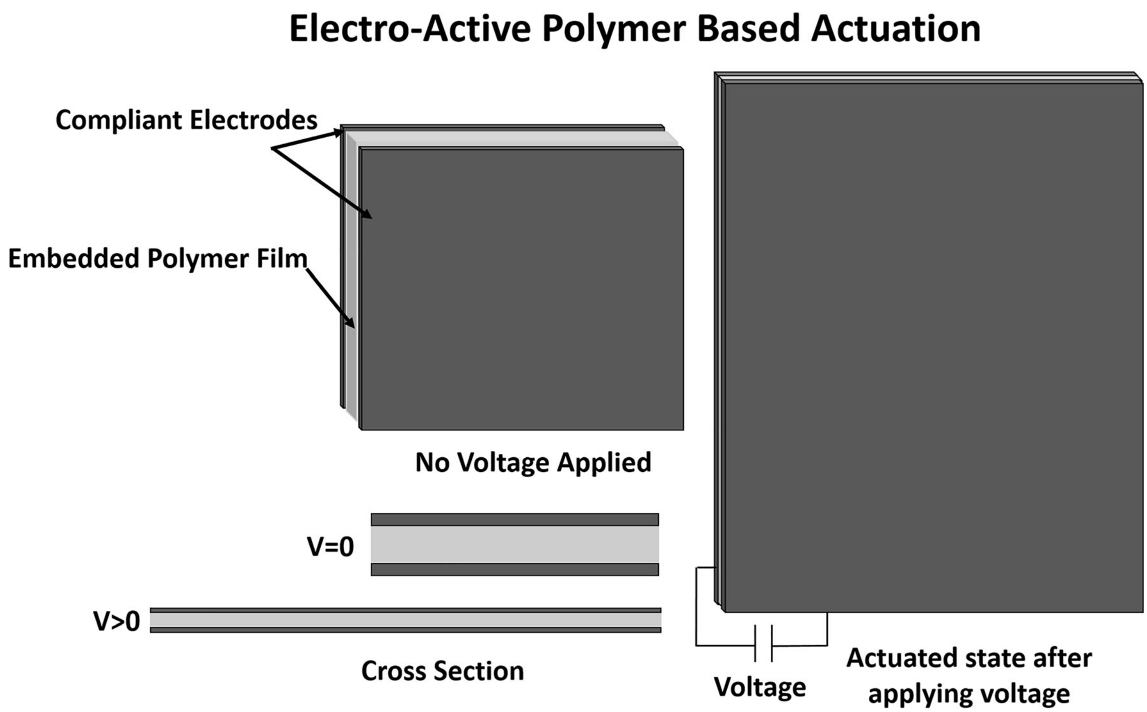

Fig. 6 Working principle of electroactive polymer actuation

Table 6 Applications, operating mechanisms, and performance parameters of cited papers related to electro-adhesive actuation

Authors	Applications	Operating mechanism	Performance parameters
Guo et al. (2018) [39]	Pick and place of different objects	1. Upon applying voltage, the Maxwell stress was generated which resulted in the bending of the gripper, while at the same time, due to the electric field being built around the object to be grasped, the gripper sticked to the objects and gripped it tightly	• By applying stepped voltage from 1 to 5 kV to the gripper, a monotonically increasing capacitance was measured • Gripper was not only capable of sensing proprioceptive and exteroceptive stimuli but also of morphing to concave surfaces
Guo et al. (2018) [40]	Gripped complex-shaped objects	1. Authors combined the benefits of pneumatic actuation and EA for designing the gripper which helped in minimizing the limitations offered by each actuation individually	• PneuEA gripper handled not only flat and flexible materials but also complex-shaped objects • No performance parameters have been reported
Alizadehyazdi et al. (2020) [41]	Grasped wine glass, soccer ball, orange, and a lamp	1. Combination of gecko adhesion with EA helped in getting a firm grip	• Adding two adhesives improved the gripping capabilities across acrylic, Tyvek fabric, and Kapton hemispheres of different diameters on an average of 100%, 39%, and 168%, respectively
Chen et al. (2019) [42]	Pick and place of thin, flat and complex-shaped objects	1. Benefits of Fin-Ray effect and EA were combined 2. Two Fin-Ray structured fingers were equipped with two EA pads	• 65% more weight in shear was lifted by the FinEA gripper when 4 kV was applied compared with 0V • Gripper could lift acrylic spheres with diameters from 120 (642 g) up to 300 mm (694 g) when 4 kV was applied to the EA pads • With EA off, the maximum lifted sphere diameter was 250 mm
Xiang et al. (2018) [43]	ContinuumEA was designed for grasping objects in complicated environments	1. EA gripper had been combined with continuum arm made of six bellow actuators 2. Bellow operates as a linear actuator. When inflated, the bellow extends. Movement of each section of the continuum arm was controlled by relative inflation of the three bellows. Continuum arm realized both bending and elongation movements this way	• Experiments showed that both shear EA forces and normal EA forces increased as the applied voltage increased

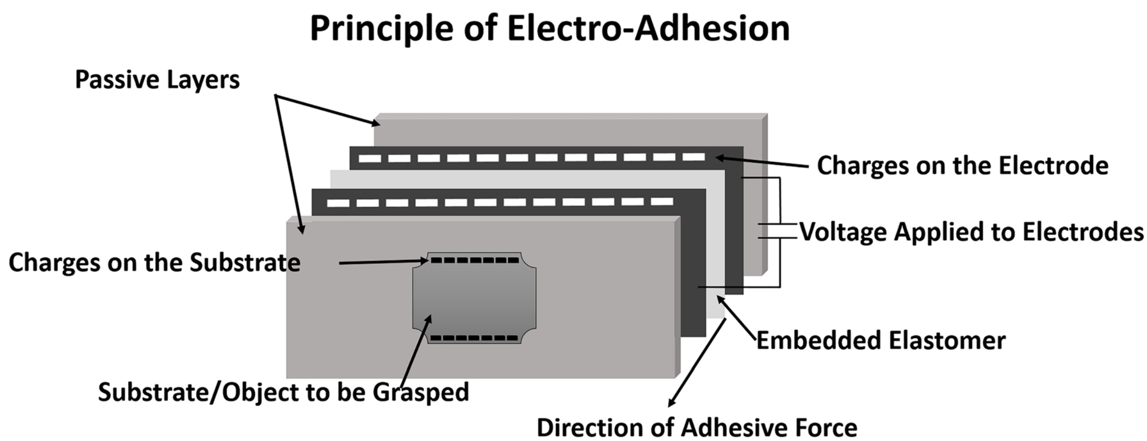

Fig. 7 Working principle of electro-adhesive actuation

to develop their shape-adaptive monolithic soft gripper which had both proprioceptive and exteroceptive sensing [43]. Guo et al., in another work, combined the benefits of both pneumatic actuation and electro-adhesion in their gripper. This combination helped in minimizing the limitations offered by each actuation individually as this gripper was able to lift objects of flexible materials as well as of both simple and complex shapes. Also it was able to lift objects from non-planar surfaces [44••]. Alizadehyazdi et al. combined the gecko adhesion with electro-adhesion to make the grasp of the gripper stronger [45]. Chen et al. developed two Fin-Ray structured fingers equipped with two electro-adhesive pads for their gripper. This soft gripper was shape-adaptive and could lift both convex- and concave-shaped objects and also of small and large sizes [46]. Xiang et al. developed a soft continuum manipulator for performing pick and place operations in complex environments by using the EA-based end-effector. This manipulator was able to handle delicate and soft objects easily [47].

Other Types of Actuation

Besides the above discussed technologies, several other actuation methods have been used by researchers (Table 7). Electric actuators based on handed shearing auxetics (HSA) were employed by Chin et al. in their soft gripper. HSA-based actuators can both twist and extend upon applying angular input owing to their auxetic design. Their gripper integrated three modes of grasping: parallel jaw, suction, and soft fingers. For the mode of suction, suction cups were incorporated

Table 7 Applications, operating mechanisms, and performance parameters of cited papers related to other types of actuation

Authors	Applications	Operating mechanism	Performance parameters
Chin et al. (2020) [44••]	Grasping of different objects	1. Each finger of the gripper used a pair of HSA cylinders driven by servo motors for actuation	• Gripper grasped 88% of 75 different tested objects, 14% of which were grasped using a combination of grasping modes • Grasping forces for each mode are listed in Table 01 of the paper Chin et al. [44••]
Yang et al. (2020) [45]	Pick and place demonstration was performed for a fragile fruit (strawberry)	1. SCP generated significant mechanical power in a muscle like form upon electrical activation by Joule heating 2. Using SCP actuator for actuation of Fin-Ray gripper made the whole structure lightweight and compact	• Experiments showed that the fingertip distance to voltage relationship showed a good linearity • Desirable distance is obtainable by adjusting the applied voltage input
Choi et al. (2020) [46]	Used to handle/grip diverse arbitrary objects	1. Material hardened upon applying magnetic field thereby increasing its gripping property while avoiding damage of the grasped object at the same time	• For SMRE: i. Measured response time =11 ms ii. Recovery time = 19 ms
Véronneau et al. (2020) [47]	MR actuated supernumerary robotic limbs (SRL)/wearable extra limbs	1. Arm and the gripper were powered through MR clutches and hydrostatic transmission lines 2. MR clutches minimize the actuation inertia to provide fast dynamics and good back-drivability	• Experimental open-loop force-bandwidth at each joint = 18 Hz • Maximal speed reached by the device end-effector is 3.4 m/s • First two joints provide 35 Nm, and the third joint provides 29 Nm

into the fingertips of the gripper [48]. Yang et al. used super coiled polymer (SCP), an artificial muscle formed by twisting nylon fibers, for actuating a robotic manipulator comprising of a robotic arm and a Fin-Ray effect–inspired gripper. The gripper was able to handle fragile and delicate objects [49]. Using magnetorheological (MR) fluids in soft grippers introduced a new direction to actuation. Choi et al. developed a gripper that changed its shape according to the object it grasped. Shape-adaptive MR elastomers (SMRE) were attached to the gripper. No sensors were used in this design. A good response time comparable to the industrial applications was obtained [50]. The use of MR technology was also made by Véronneau et al. for powering supernumerary robotic limbs (SRL) which are wearable extra limbs. The SRL developed in this work had 3 DoF and a three-fingered gripper. Both the arm and the gripper were powered through MR clutches and hydrostatic transmission lines. During the experimentation, the gripper exhibited efficient speed, while the torques obtained by the arm's joints were more than sufficient to hold manual industrial tools [51].

Discussion and Conclusion

Actuation is a major challenge in general in soft robotics, as without a proper actuation technology, the desired functionality cannot be achieved. At the same time its mechanical design should not affect the soft nature of the device. Soft grippers and manipulators make no exception, and a trade-off is necessary. Pneumatic actuation is the widely used technology as it provides high grasping forces and gives control to the user to attain the desired shape of the actuator. These actuators have no problem of friction and are quick in response. Moreover, the control is easy that is why it is more commonly used over the other methods. However, it is difficult to miniaturize them, and they are easy to fail during trials due to leakages. Also their manufacturing is not simple as they are made in various stages. Cable-driven actuation is also listed as a well-established technology as it provides good force and moment control. In biomedical applications, this technology is preferred owing to the fact that the cables can be pulled at any time out of the body in case of any problem. Cable-driven actuation offers good response speed, motion accuracy, flexibility, and adaptability; however, energy loss due to friction between cables is a limitation.

The shape-changing property due to temperature stimulus has made SMAs popular in driving different soft systems. High power-to-weight ratio SMAs can be easily driven by electric current through ohmic heating. They produce low noise, have low driving voltages, are small in size, provide high distortions and smooth movements, and possess simple structures. However, owing to their slow response, they are not preferred in applications that demand quick response. They also have poor fatigue characteristics. Vacuum actuation is another used technology mainly for suction or in applications where variable stiffness is desired. Negative pressure in vacuum actuators provides a fail-safe feature in comparison to pneumatic actuators. They shrink upon actuation that makes them suitable for small space applications and improves the actuators' lifetime and durability. However, miniaturization is a problem for them, and in case of jamming, they demand a dexterous design. EAPs possess the strengths of having high actuation pressure, short response time, high expansion efficiencies, low energy consumption, conformable grasping, and being lightweight. However, these actuators normally generate low forces, cannot pick heavy objects, and require high voltage for their actuation. Electroadhesion has the benefit of giving a firm grip to the objects. This type of actuation is silent. The EA actuators can easily handle lightweight objects, have simple design, and are electrically controllable. However, they are not typically effective on rough surfaces. Also planar EA grippers have difficulty in picking curvy objects and in adhering to non-flat surfaces. This is the reason why many authors have used EA-based actuation but always in combination with other actuation technologies.

Each actuation technology has its own merits and drawbacks. The selection is mainly based on the application. The most optimized solution has to be chosen such that the required purpose of the design gets fulfilled. From the literature used in this paper, the main observation was that most soft grippers and manipulators are mainly tested in the laboratory particularly for pick and place operations and handling of delicate as well as complex-shaped objects. Very few of them made it to the field. Therefore, a lot has to be done yet for developing soft grippers and manipulators for the industrial applications. Another point worth mentioning is that since pneumatic, vacuum, and cable-driven actuations have widely been used by the researchers owing to the fact that they possess more advantages over the other available technologies, this has improved their reliability. The technologies including SMAs, EAPs, and EA are still in a growing stage, and it will take time for them to be mature. However, they can be integrated with the pneumatic, vacuum, or cable-driven technologies such that a more efficient and reliable system could be developed.

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Declarations

Conflict of Interest The authors declare no competing interests.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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- •• Of major importance

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