Proceedings of CONF-MLA 2026 Symposium: Intelligent Systems and Automation: AI Models, IoT, and Robotic Algorithms
DOI: 10.54254/2755-2721/2026.LD38742

From Structural Mimicry to Functional Biomimicry: Research Progress in Sensing–Actuation Fusion Mechanisms for Soft Grippers

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Abstract. A soft gripper can deform around an object, yet deformation by itself tells the operator little about whether that object is held securely. This review is concerned with the ways in which grippers obtain that missing information, i.e. how sensing is coupled to actuation. It first draws on the human hand, octopus tentacles, plant tendrils and several other organisms, whose grasping involves coordinated fingers, contact receptors distributed over the body, or stiffness that changes after contact. Designs are then organized according to where the sensing element sits relative to the actuator: a separate module linked through a controller, a flexible sensor embedded in or attached to the actuator, or a sensing function provided directly by the active material. Actuation and sensing methods, together with variable-stiffness and control schemes, are discussed in terms of the working conditions each one tolerates. Examples drawn from produce handling, rehabilitation and industrial sorting are used to show why a given architecture suits a given task. Load, measurement accuracy and reliability over repeated cycles, along with the hardware these functions require, still restrict practical use. Closer integration is expected to come from multifunctional materials and data-driven control, although comparing such designs will require test protocols that studies do not yet share.

Keywords: soft gripper, biomimetic design, sensing–actuation fusion, flexible sensor

1. Introduction

Rigid grippers remain the standard choice on automotive, electronics and logistics lines, where the kinematics are known in advance and accurate position control gives repeatable motion together with high load in a structured workspace [1]. That advantage weakens as soon as the object's shape, surface or position is no longer fixed. A finger with no room to give when it meets an unexpected surface will either mark the object or fail to hold it. Tasks such as picking fruit, handling food, working with delicate tissue or operating underwater consequently ask for more compliance at the contact than a conventional factory task does [2].

Soft grippers meet that requirement by building the load-bearing structure itself from a compliant material, commonly silicone rubber, another elastomer or a hydrogel. Because the fingers wrap rather than meet the object at fixed points, part of any positioning error is taken up mechanically,

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DOI: 10.54254/2755-2721/2026.LD38742

and less is demanded of the sensors and motion system before contact [3]. These grippers are also light and comparatively easy to fabricate, though how far such benefits hold depends on the material and actuator in question. Xu et al. [4] report that design is moving in this direction, toward treating materials, structures, actuation and sensing as one problem. Their somatic design view asks how the parts support a grasp jointly, instead of assessing each part on its own.

The same compliance is what makes the state of a soft gripper hard to estimate and its force hard to regulate. A fixed model is difficult to keep accurate when the material is hyperelastic, deformation is large and the contact keeps changing; parameters also drift with fabrication tolerances and ambient conditions [3]. Many early grippers were simply commanded to a pressure or displacement, and the contact that resulted was not measured. Passive adaptation may still produce a grasp in this way, but the controller learns nothing about the force applied or whether the object is beginning to slip. Integrating sensing with actuation is meant to close that gap: deformation and contact are monitored while the gripper moves, and the readings are fed back to the actuator [5]. The difficulty lies in doing so without stiffening the structure and losing the compliance that was the reason for using it.

Biology offers working examples of precisely this arrangement. In the hand, bones, muscles and tendons generate movement, and mechanoreceptors in the skin report the contact. The octopus builds no skeleton at all; its tentacle is a continuous body studded with suckers, much of the control handled locally. A plant tendril coils on contact and only later stiffens to hold the support [2]. The functions an engineer can take from these are not the same: the hand suggests articulated movement paired with touch, the tentacle suggests sensing spread along a continuous body, and the tendril suggests a hand that is soft when it first contacts and load-bearing once settled. A gripper follows these relationships either by carrying sensors within its actuator or by letting the actuator material sense on its own [5].

Where the sensing element is placed offers a convenient basis for telling these designs apart. In a discrete system, a camera or a separate force sensor exchanges information with the actuator through a controller. A flexible sensor that is bonded to the surface or embedded instead shares the actuator's own structure, so local contact and deformation can be read directly. With intrinsic unification, one goes further and uses an electrical or ionic property of the active material as the state signal. The point of setting the three arrangements side by side is to see what each can measure and what has to be added to obtain that measurement.

The discussion proceeds along these lines, from the biological example to the engineered device. Grasping mechanisms taken from hands, octopus tentacles, tendrils and other organisms are examined in Section 1. Section 2 sets the discrete, structurally integrated and intrinsic approaches against one another. Actuation, sensing, stiffness adjustment, control and reported performance are taken up in Section 3. Section 4 connects these technical choices with agricultural, medical and industrial settings and the constraints that remain in each, after which Section 5 states the conclusions and the work still to be done.

2. Biomimetic grasping mechanisms

Organisms do not make contact, spread load or hold on to a support in the same way, and the examples below are chosen to map those functions onto gripper design. Coordinated fingers come from the hand; the wrapping of a continuous body and the sensing that goes with it come from the octopus; a tendril contributes coiling followed by reinforcement. What is worth taking from these models is not only the outer form but the way movement and touch work together.

DOI: 10.54254/2755-2721/2026.LD38742

2.1. Human hand-inspired multi-finger grasping structures

Grippers inspired by the hand are built with several compliant fingers, which produce a number of contact points around the target. The fingers may be driven pneumatically, by tendons or by a smart material, and their number and layout allow pinching, wrapping and hooking as the object requires [4]. Liu et al. [6] paired silicone rubber fingers with SMA modules to reproduce the way a compliant muscle and a load-bearing bone complement each other. The finger is compliant when it first bends around the target; the SMA then undergoes its phase transformation and stiffens the structure. A single finger reached a fingertip force of 1.7 N, 112.5% higher than the conventional soft finger used as the comparison. Shape adaptation and force support thus occur in one finger, one after the other.

Cutting a finger into segments adds another means of controlling the contact. Wu et al. [7] drove the proximal, middle and distal segments on their own, varying the pressure combination for grasping and for manipulating an object already held. Capacitive pressure sensors made from ionic nanofibres were laid over the finger surfaces to provide touch feedback and assist object recognition. A different route was taken by Xiao et al. [8], who placed airbag-driven rigid skeletons inside pneumatic soft actuators. The resulting rigid-soft coupling actuator held up to 34.21 N and took in objects from fragile fruit to 5 kg loads. The two studies show how different kinds of structural support can widen what a compliant finger is able to do.

2.2. Octopus tentacle-inspired continuum enveloping

An octopus tentacle has no rigid skeleton; it bends, elongates and twists by means of a muscular hydrostat, and suckers spread over its surface give the wrapping contact additional adhesion. Engineered tentacles are usually long continuous bodies actuated by several pneumatic chambers or by tendons, which lets them coil around irregular objects [9]. One fully stretchable version, reported in 2025, carried triboelectric sensors based on carbon nanotubes together with strain sensors, and multimodal units were placed in eight of the suckers [10]. The signals were interpreted by machine learning for material recognition and spatial mapping, so the design reproduced the distributed sensing of the original and not merely its outline.

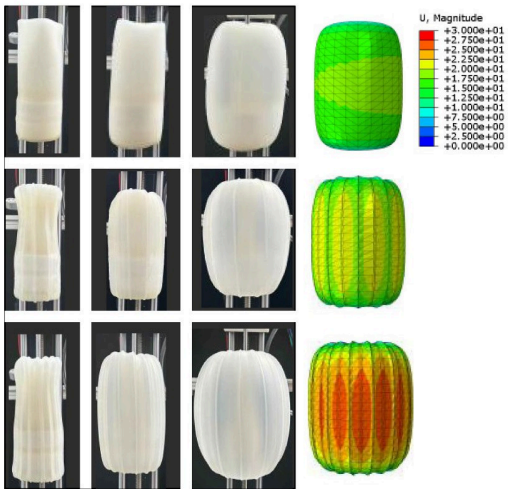


Figure 1. Structure and grasping modes of the multimode inflatable toroidal soft gripper inspired by sea anemone swallowing behavior (reproduced from Xiang et al. [12])

DOI: 10.54254/2755-2721/2026.LD38742

An octopus-inspired arm reported in 2026 located sensing at each sucker and organised the units under a hierarchical controller for autonomous grasping underwater [11]. Every sucker held an LED and a phototransistor, the reflected light giving both contact force and direction. Sensitivity was around 400 mV/N over 0-2 N, the direction error stayed under 18 degrees, and the units worked wet as well as dry. Feedback was therefore available at points all along the continuous body. Fig. 1 shows a related case of large-deformation grasping, the sea anemone-inspired gripper of Xiang et al. [12]; an inflatable toroid with V-shaped folds lets it move between swallowing, enveloping and expansion modes.

2.3. Plant tendril-inspired helical coiling

A tendril does not stay at a fixed stiffness. It coils once contact is made and only then builds the stiffness required to bear the plant's weight, and grippers modelled on this sequence tend to be strip-like bodies in which offset pneumatic chambers, or an anisotropic material, drive helical bending around an elongated object [13]. Wei et al. [14] reported a double-layer pneumatic coil-wrap gripper in 2026. Its main chamber followed the contour of the target, while an auxiliary chamber at the end raised the local pressure after wrapping; the inner and outer layers were given different friction coefficients, which produced frictional self-locking and improved both attachment and load capacity.

The stiffness change itself was reproduced by Must et al. [15] with reversible osmotic actuation, in a tendril-like robot only about 1 mm across. The concentration of osmotic agents was set by ion electroadsorption at flexible electrodes, giving rotation together with a reversible stiffness increase of roughly five times. Because the effect arises in the material, actuation and the adjustment of stiffness are delivered together; the device mirrors the move from a soft coil to reinforced attachment without calling on a separate rigid support.

2.4. Grasping inspiration from other biological prototypes

Some models are of interest for the area they bring into contact, others for their speed. Hao et al. [16] took the chameleon's strike as the basis for a pneumatic enveloping gripper, in which changing the chamber pressure swells and contracts the body and enlarges the contact with targets of different shapes. For rapid grasping, Cai et al. [17] turned to bird claws: an elastic buckling actuator is driven through snap-through by negative pressure, and bistable fingers open and close quickly with little energy, extension and bending taking about 110 ms and 115 ms. A pair of infrared sensors locates the target and starts the grasp without intervention.

Lampreys suggested a pneumatic layout in which an upper positive-pressure chamber and a lower negative-pressure suction chamber act together to steady the grasp [18]. Another gripper, modelled on eagle claws and skin, used liquid-metal TENG sensors for active perception [19]. The adhesion of gecko feet and the hexagonal friction pattern on frog toes have likewise been built into contact surfaces meant to hold in dry and wet conditions. Wrapping, adhesion, rapid closure and contact sensing all recur across these cases, but a transferred feature is only as useful as the way it is combined with the others; close resemblance to the organism is not what makes the gripper work.

3. Sensing–actuation fusion approaches

The classification used here rests on the physical relation between the sensing unit and the structure that moves. Modules that are kept apart and made to exchange information through a controller form a discrete system. A sensor mounted on the actuator or embedded in it, while still functioning on its

DOI: 10.54254/2755-2721/2026.LD38742

own, gives a structurally integrated system. In the unified case the active material itself produces a signal that varies with its state. Framed this way, the three can be compared for the feedback each makes available, the interfaces they require and the limits met in use.

3.1. Discrete sensing–actuation systems

In a discrete system the sensor and actuator remain physically apart, an external controller connecting the two, so each module can be chosen and developed independently. A camera mounted outside, for instance, reports where the target is and what shape it has without altering the finger. Those measurements say little about local finger deformation or contact force, however, and the additional hardware makes the whole system larger [4]. Early soft grippers were commonly arranged in this way, vision setting the planned posture and the finger then driven to it.

Kai et al. [20] pointed a camera at the object and gripper before contact and used a flexible-finger deformation model to predict where contact would occur and with what force, which allowed the stability of candidate postures to be judged. For irregular food items, Li et al. [21] combined visual geometry with data-driven grasping prediction and configuration optimization; their fruit and vegetable experiments gave a 97.7% success rate. External measurements serve planning well in these systems. They do not, unless contact is also sensed, describe the force distribution or the deformation of the finger while the grasp is under way.

Independent force sensors or tactile arrays are sometimes fixed to the outside of an otherwise discrete gripper to supply the contact information it lacks. The system of Mohamed et al. [22], built for harvesting baby broccoli, used TPU flexible fingers together with a separate module reporting force in real time; the grip was adjusted to the stem as a result, and trials gave a 94% success rate with 97% of heads harvested without damage. Putting the sensor outside does make the contact force available, but the coupling between sensor and compliant structure tends to disturb the reading, and the added module makes the system more complex and bulkier.

3.2. Structurally integrated sensing–actuation

A structurally integrated gripper places the flexible sensor within the soft actuating structure itself-embedded, attached or conformed to the surface-which brings sensing and actuation close together in space even though the two remain separate in material and function. Local deformation and contact can then be measured at first hand, and the distance a signal has to travel between contact and control is shortened; this is now the mainstream route to sensor fusion in soft grippers [23]. Where exactly the sensor is integrated gives three variants: attached to the surface, embedded inside, or conformed to the structure.

Working under negative pressure, the gripper of Xiang et al. [24] carried visual markers and pressure sensing, the deformation of its compliant structure indicating target size together with grasping and contact forces during gentle handling. Reinforcing ribs were added to the buckling structure on the basis of finite element analysis, which raised the largest negative pressure it could sustain from 10.68 kPa to 16.36 kPa. The capacitive pressure sensors of Wu et al. [7], electrospun from ionic nanofibres, were placed over multi-segment fingers; their conformal fit kept the pressure readings usable under large deformation and gave feedback for touch perception and object recognition.

DM-BioGrip, reported by Kuang et al. [25] and shown in Fig. 2, is built around 6 proprioceptive sensors and 28 exteroceptive ones, the former following the bending of joints and the latter contact with the object. Its sensing material, a CB/silicone composite loaded at 6 wt%, stretched beyond

DOI: 10.54254/2755-2721/2026.LD38742

300% while remaining highly sensitive. A dual-channel 1D-CNN fused the signals and recognised objects with 99.7% accuracy over 900 grasps spanning 18 target types. To keep bending from interfering with contact pressure, Dong et al. [26] introduced hemispherical microstructures and H-shaped liquid-metal microchannels, reaching a bending-to-pressure sensitivity ratio of 47.5:1; random-forest classification of tomato diameter, height and weight on a three-finger gripper gave 99.05%, 98.10% and 99.05%. Embedded sensing is informative in these examples, which also make clear that separating signals, matching sensor to elastomer and surviving cycles are problems still to be handled.

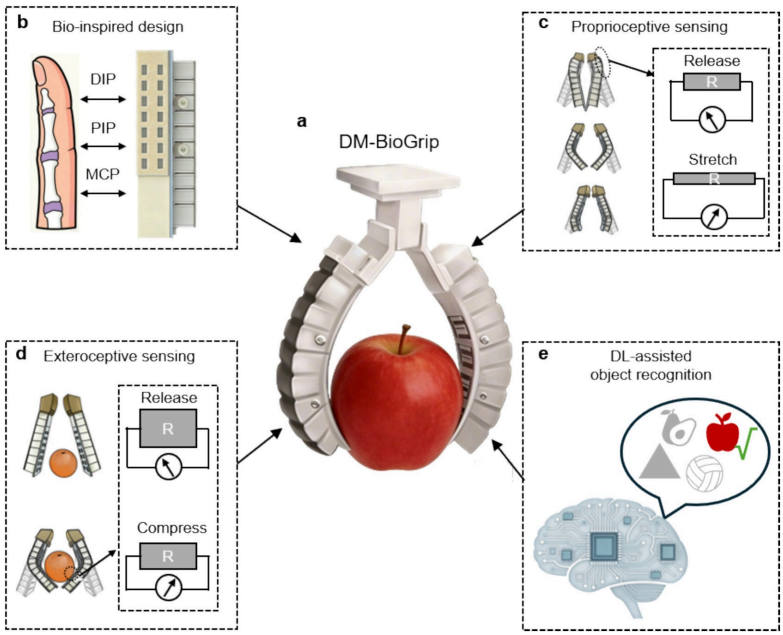


Figure 2. Structure and sensing fusion framework of the biomimetic multi-joint soft gripper DM-BioGrip integrating proprioceptive and exteroceptive sensors (reproduced from Kuang et al. [25])

3.3. Intrinsic sensing–actuation unification

Intrinsic unification takes a property of the active material that changes with its state and uses that property as the sensor signal. The signal may be the capacitance of a dielectric elastomer, the resistance of a conductive composite, the ionic conduction of a hydrogel or the electrical response of a deforming liquid metal [5]. One material then both actuates and reports how it is responding, which removes the need for a separate sensing element and the interface that would come with it. Recovering the deformation signal while that same material is being driven is the problem at the centre of this approach.

Apply a voltage to a DEA and it contracts, and the same deformation alters its capacitance as the electrode area and dielectric thickness change; capacitance measured in real time therefore gives the actuator's state, i.e. self-sensing. HASEL artificial muscles add hydraulic coupling to the electrostatic mechanism, which gives contraction comparable to a biological muscle together with self-sensing of deformation and recovery from electrical damage, and they are regarded as an important route to intrinsic unification in grippers [27]. A monolithic gripper driven photo-thermally was reported to separate electro-tactile sensing from photo-thermal actuation by zoning the structure along biomimetic lines. A central sensor and surrounding actuators were screen-printed as a double-

DOI: 10.54254/2755-2721/2026.LD38742

layer film on one substrate, the sensor covering 0-2500 kPa, responding in 5 ms and lasting beyond 40,000 cycles [28].

Hydrogels are of particular interest here because they conduct ions and are biocompatible. One asymmetric multilayer hydrogel muscle, reported in 2025, combined a thermoresponsive hydrogel that actuated, copper-wire heaters laid in serpentine paths for control and strain-responsive hydrogel sensors for deformation, all within a system that remained soft throughout and reported its own actuation state [29]. A review published in 2026 observes that the field is moving sensing functions deeper into actuating materials and structures-liquid-metal flow, for instance, is used to govern resistance and heating so that a gripper grasps and releases with no external sensor [5]. Output force is still limited, driving voltages are high, accuracy drifts with the environment and material stability is incomplete, so unified grippers are not yet ready for use at scale.

4. Key technologies and performance comparison

How a soft gripper performs depends jointly on several technologies-the way it is actuated and sensed, whether its stiffness can be varied, and how it is controlled-and different routes weight output force, response, compliance, accuracy and complexity differently. The chapter compares these technologies with a view to the choices involved in designing and selecting a gripper.

4.1. Actuation methods

Pneumatic actuation is the most common in soft grippers, compressed air being admitted to, or withdrawn from, elastic chambers to produce deformation. It offers a simple structure, substantial output force, safety and low cost, but the external air source and tubing make the system less portable and the compressibility of the gas stands in the way of precise control [3]. The best-known actuator is PneuNet, a series of chambers connected in sequence that bend as they expand under pressure. Kumar et al. [30] optimised such grippers topologically with the pneumatic load treated as design-dependent, coupling Darcy's law with the method of moving asymptotes to shape the chambers automatically; a four-finger gripper was then made by SLA 3D printing, and the optimised chambers deformed up to 86.98% more than conventional rectangular ones (Fig. 3 shows the chambers and their fabrication). For fin-ray-effect grippers, Wang et al. [31] built a contact-induced rotational statics model that includes external loads at several positions and the target's geometric constraints, which predicts finger deformation and contact force without sensors and uses grasping force over several target sizes to set the link parameters.

Negative pressure gives a route distinct from inflating chambers. Cai et al. [17] used vacuum-driven buckling to produce snap-through in around a hundred milliseconds. The gripper of Li et al. [32] had a micro air pump built into a variable-structure body, channels on the finger cups controlling the airflow in both directions so that no external source was needed. EAP actuation, covering dielectric elastomers and HASEL devices, responds quickly and can sense itself, although voltages of several thousand are normally called for [27]. SMA contracts through its phase transformation; Liu et al. [6] combined it with pneumatic actuation to adjust stiffness, at the cost of slow response, low energy efficiency and a limited cyclic life. Hydrogels that respond to temperature and SMPs are also candidates for compliant medical devices, their responses being generally slow [29].

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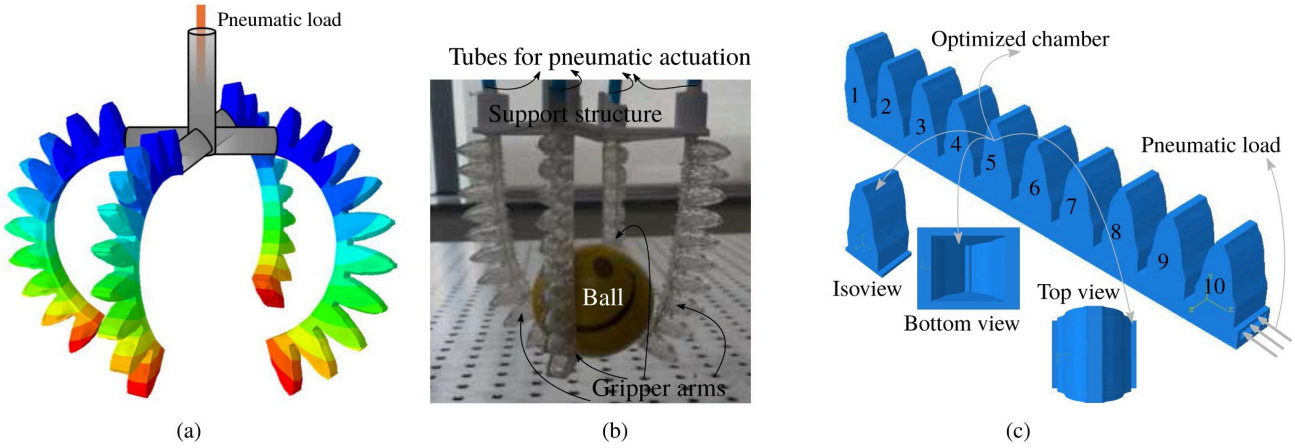


Figure 3. Pneumatic chamber structure and 3D printing fabrication of the soft pneumatic gripper based on topology optimization design (reproduced from Kumar et al. [30])

4.2. Flexible sensing methods

A resistive sensor turns deformation into a change in resistance within a conductive material, and the straightforward readout helps explain why the type is used so widely for strain and pressure in grippers [23]. The CB/silicone sensors of Kuang et al. [25] and the liquid-metal microchannels of Dong et al. [26] both work this way. Capacitance is used differently: electrode spacing or the dielectric changes under load, the sensors draw little power, drift little with temperature and can be laid out in arrays. In the ionic nanofibre sensors of Wu et al. [7], the electric double layer that forms at the gel-electrode boundary is what raises the sensitivity to pressure.

Light is the measurand in optical sensing, deformation appearing as a change in intensity, phase or wavelength. Because such sensors ignore electromagnetic interference and can take measurements at several points, they suit contacts near which electronics cannot be placed. The gripper in [33] ran on hybrid optical fibres that read finger bending and contact force while every electronic part stayed outside the body, which let the gripper work under strong radiation and at high temperature. Piezoelectric and triboelectric types draw their signal from dynamic loads and can report slip or a changing force; the skin-inspired sensors of [34] exploited cracks and stress concentration to sense the onset of slip and shear, the grip being tightened before the object could escape.

4.3. Variable stiffness technologies

Compliance is wanted while contact is being made and stiffness once the object is carried, and one fixed stiffness rarely meets both stages. Variable-stiffness designs alter the mechanical response after the fingers have already conformed to the target [4], the available means ranging from particle or layer jamming to shape-memory alloys and polymers and to magnetorheological or electrorheological fluids. Which means fits depends on the speed at which stiffness has to change and the supporting hardware a task can accommodate.

With particle jamming, particles held in a flexible chamber lock against one another under vacuum to give a rigid body and loosen back to a soft state when the pressure returns, the result offering a wide stiffness range from a simple structure. One gripper based on differential-drive jamming used two deformable chambers, only one filled with particles, bending and stiffening being decoupled through the pressure difference between them [35]. Layer jamming relies on the friction

DOI: 10.54254/2755-2721/2026.LD38742

that builds between thin sheets under negative pressure; the gripper in [36] paired such a structure with electroadhesion so that stiffness and deflection were obtained at once. Where Liu et al. [6] used SMA, the phase transformation contracted the alloy and stiffened the finger, raising the single-finger fingertip force by 112.5%. Xiao et al. [8] instead held posture and force by letting a rigid skeleton lock mechanically, with a holding force up to 34.21 N; Fig. 4 shows the actuator and the ways it operates.

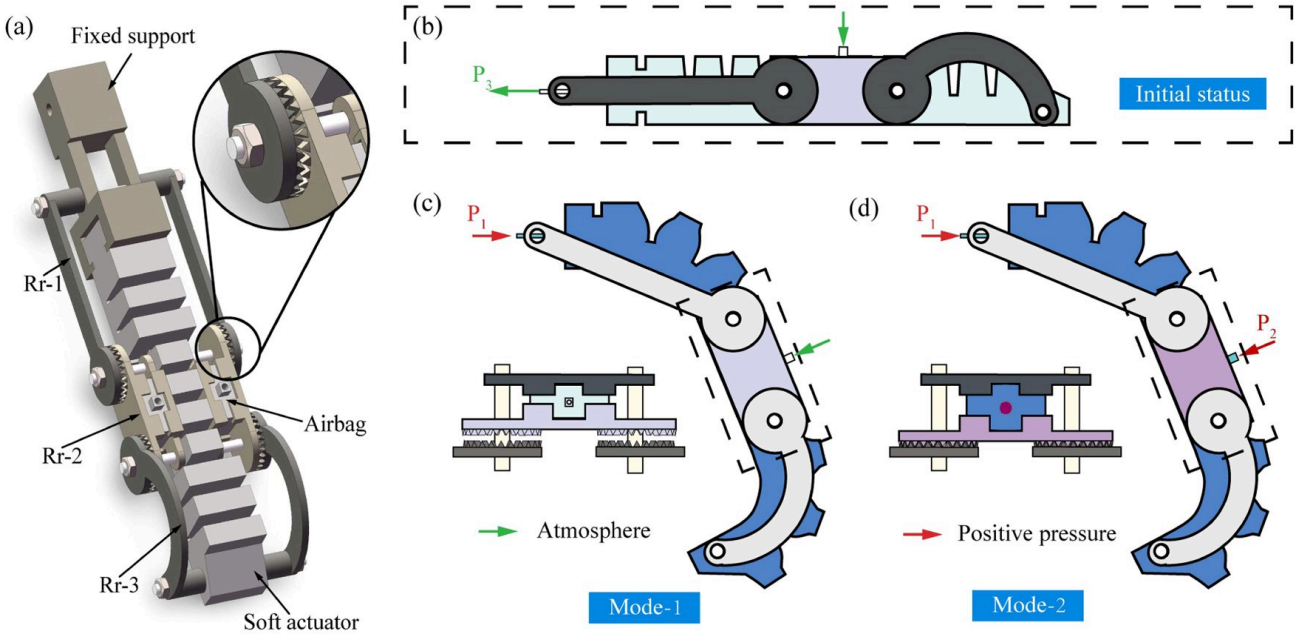


Figure 4. Structure and working modes of the rigid–soft coupling bending actuator with mechanical self-locking mechanism (reproduced from Xiao et al. [8])

The supporting hardware is not the same from one method to the next. Jamming with particles or layers calls for a vacuum source; SMA and SMP elements dispense with it but take longer to respond, and rigid-soft coupling trades added mechanical complexity for a larger force. The choice has to be made for the task, balancing response time and output force against energy use and the room left for the complete system.

4.4. Closed-loop control and intelligent sensing

In feedback control the actuator command is revised from the measured state of the grasp, and because large deformation and uncertain contact make regulation from a fixed model difficult, data-driven methods have been drawn in. Kuang et al. [25] fused proprioceptive with exteroceptive signals in a dual-channel 1D-CNN for object recognition, while the random forests of Dong et al. [26] mapped bending signals on to tomato size and Li et al. [21] joined grasping prediction to configuration optimization. Recognition and planning are supported by these methods; whether they close a feedback loop depends on whether the estimated state is in turn used to change the actuation.

When feedback arrives matters as much as what it contains. Kai et al. [20] judged stability before contact from images and a deformation model. Slip sensors report only after contact and permit the force to be raised as stability starts to go [34]. The gripper in [37] paired an active palm with high-resolution visual sensing and compliant fingers that could be reconfigured, tactile arrays at the fingertips supplying the contact information needed for adaptive grasping and manipulation. Read in

DOI: 10.54254/2755-2721/2026.LD38742

order, the cases separate planning before contact from correction during it and indicate where multimodal sensing enters at each stage.

4.5. Performance evaluation and comparison

Table 1 sets representative designs against one another for actuation, sensing, stiffness adjustment, the force or other performance reported and the application. Fingertip force and holding force do not measure the same thing as recognition accuracy or response time, each describing a different side of performance; with targets and test conditions differing between studies, the table is a comparison of design choices rather than a ranking.

Table 1. Performance comparison of representative soft grippers

Reference	Actuation	Sensing	Variable Stiffness	Output Force /Performance	Application
Liu et al. [6]	Pneumatic + SMA	None	SMA phase transformation	Fingertip force 1.7N	General grasping
Wuet al. [7]	Pneumatic multi-segment	Nanofibercapacitive	None	Multi modegrasping	Industrial sorting
Xiao et al. [8]	Pneumatic rigid-soft coupling	None	Mechanical selflocking	Holding force 34.21 N	Heavy-loadgrasping
Kuang et al. [25]	Pneumatic multi-joint	CB/siliconeresistive	None	Recognition rate99.7%	Object recognition
Dong et al. [26]	Pneumatic	Liquid metalbending	None	Classification rate99.05%	Agricultural sorting
Xiang et al. [24]	Negative pressure pneumatic	Visual markers +pressure	None	Negative pressure16.36 kPa	Agricultural product grading
Cai et al. [17]	Negative pressure buckling	Infrared sensor	Bistable	Response ~110 ms	Fast grasping
Xiang et al. [12]	Positive pressure pneumatic	None	None	Three-modes witching	General grasping
Kumar et al. [30]	Pneumatic topology optimization	None	None	Deformation improvement 86.98%	Design optimization
HASEL[27]	Electro-hydrauliccoupling	Capacitive selfsensing	None	Self-sensing, selfhealing	Artificial muscle

Most rows of Table 1 use pneumatic actuation, but the sensing and stiffness arrangements change with the task. An accuracy figure describes sensing or classification, a force figure describes mechanical output, and the two ought not to be read as interchangeable signs of how well a gripper grasps. Evaluation would be easier to compare if studies reported success rate, maximum load, the smallest object grasped, cyclic life, sensing accuracy and response time under conditions they state; the hardware and control that integration adds would then be plainer as well.

DOI: 10.54254/2755-2721/2026.LD38742

5. Typical applications, existing problems, and development trends

5.1. Agricultural harvesting and food processing

Harvesting is among the applications where soft grippers are most expected to help, fruit and vegetables being irregular in shape, easily damaged and far from uniform in maturity. A rigid grip readily causes mechanical injury, whereas the compliant enveloping of a soft hand can hold the crop without injury and keep the grasp steady. For baby broccoli, Mohamed et al. [22] built a TPU hand with force feedback that adjusted the grip to the stem, giving a 94% success rate and leaving 97% of heads undamaged. The four-finger gripper of Li et al. [32], which triggers on colour and distance and varies its own structure, combines compliant enveloping with adsorption to take fruit and vegetables of different shapes; the palm moves between a cross and a parallel layout for spherical and cylindrical produce, a colour sensor and ToF sensor handle recognition and short-range triggering, and success averaged about 95.5%.

Once a crop is harvested, the integrated perception-grasp hand of Xiang et al. [24] estimates size while grasping without damage and so supports the grading of fragile produce by size. The gripper of Dong et al. [26], carrying a bending sensor insensitive to pressure, sorted tomatoes by size with high precision, and the autonomous posture planning of Li et al. [21] for reconfigurable hands gave a 97.7% success rate in food handling. In these systems the joining of soft hands with sensing is carrying agricultural automation beyond the grasp alone, toward perception and decision treated as one process.

5.2. Medical rehabilitation and minimally invasive surgery

Carefully regulated force and compliant contact are both demanded in medical work, which is why soft structures are being studied for surgical tools, rehabilitation devices and the delivery of therapy. A small compliant tool can, during a minimally invasive procedure, lower the contact forces that accompany access and manipulation. The needle in [38] carried a suction cup that grasped the target tissue while an incision was made in the optic nerve region; the tool units were moved through a concentric tube arrangement, so no separate arm was needed to hold the tissue.

The wearable hand robot of [39] altered the coupling between its rigid and soft parts with a magnetorheological cable drive. Activating the fluid selectively moved the device between fully actuated and underactuated states; the modes reported cover synergistic motion, adaptive grasping, independent finger control and mechanical safety, and trials showed the device helping stroke patients through grasping tasks. Compliance lowers harmful contact, yet that alone does not qualify a device for long contact with tissue, and sterilization, reliability over long use in the intended setting and accurate force control remain to be dealt with.

5.3. Industrial sorting and special operations

Objects on an industrial sorting line differ in shape and surface and vary in how much damage they can tolerate. The fin-ray gripper of Velasquez et al. [40], intended for work in multi-robot systems, lets the fingers deform passively to match a surface; finite element analysis of the support ribs selected a 45-degree arrangement for its compliance, and the design was released as open hardware for research and teaching. Multi-segment actuation and conformal pressure sensors were added by Wu et al. [7] to support several grasping modes in sorting and in human-robot interaction, the one

DOI: 10.54254/2755-2721/2026.LD38742

case resting on mechanical adaptation and the other adding measurement and actuation choices segment by segment.

Sensing hardware is constrained further underwater, at high temperature or under strong electromagnetic radiation. The hybrid optical-fibre gripper of [33] kept its electronics away from the body while still reading its mechanical state, and the octopus-inspired arm of [11] grasped autonomously underwater with optoelectronic units that worked in dry conditions as well, extending the settings in which contact feedback is available. Whether such designs hold up outside a laboratory test still comes down to durable materials, sealing and stability over long operation.

6. Conclusions

The biological models reviewed here coordinate contact, movement and sensing in more than one way. Articulated human fingers support a range of postures, octopus tentacles wrap continuously while carrying contact information at many points, and tendrils pair an initially compliant contact with later reinforcement. The architectures reproduce these relations at different levels, discrete systems keeping sensor and actuator apart, integrated systems reading local deformation and contact within the finger and unified systems taking their state signal from the active material. Pneumatic actuation still dominates the designs surveyed, electroactive and shape-memory materials respond differently, and resistive, capacitive, optical and self-powered sensors each supply a different kind of feedback. Stiffness adjustment and data-driven control extend what these hands can do, at the price of further integration.

Produce handling, rehabilitation, industrial sorting and special operations do not ask the same things of one architecture. Force support, sensing that stays reliable under deformation, precise regulation, the supporting hardware and evaluation that can be compared remain the limiting points. Progress from here means tying the choice of material and manufacturing to durability and task performance that are actually measured; multifunctional materials and data-driven control have a contribution to make only where repeatable tests of the complete hand bear out their benefit.

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