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Structural design and applications of bio-inspired soft grippers: a review

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Abstract. As robotic systems move beyond structured industrial settings into less structured domains such as agricultural harvesting, food handling, medical manipulation, and human-robot interaction, conventional rigid grippers face limitations when handling soft, fragile, irregularly shaped, or highly variable objects. Soft grippers address this problem by combining compliant materials, deformable structures, and soft actuation to conform to object geometry. Biological systems, including the human hand, bird feet, octopus arms, plant tendrils, and fish fins, offer additional design principles for morphology and motion. This review examines structural design, actuation and materials, stiffness regulation, and representative applications of bio-inspired soft grippers. Gripper architectures are first discussed in terms of discontinuous bending, continuous bending, and continuous twisting or wrapping. Pneumatic, tendon-driven, and smart-material actuation are then reviewed together with additive manufacturing and variable-stiffness techniques. Applications in flexible industrial handling, agricultural harvesting, medical manipulation, and special environments are subsequently considered. The literature indicates that the field is moving beyond the simple pursuit of greater compliance toward coordinated optimization of compliance, load-bearing capability, grasp stability, and control accuracy. Future work is likely to depend increasingly on multimodal sensing, closed-loop control, integrated structure-actuation-sensing design, and intelligent adaptive grasping of previously unseen objects.

Keywords: bio-inspired soft grippers, soft robotics, structural design, variable stiffness, adaptive grasping

1. Introduction

Grasping enables robots to interact with objects. Rigid grippers provide precision, stability, and high load capacity but often damage soft, fragile, or irregular items (e.g., in agriculture, food processing, and medicine) due to concentrated contact stresses and reliance on complex sensing and control. Soft grippers overcome this by using elastomers, compliant structures, and compliant actuation: they deform passively on contact and conform to object shape, reducing the need for exact geometric matching. Shintake et al. classified soft-gripping approaches into three categories: actuation-based, controlled-stiffness, and controlled-adhesion gripping, and emphasized that material compliance lowers the demand for precise control during complex contact [1].

Bioinspiration further informs design. Human hands and birds achieve localized bending via skeletal joints; carnivorous plants bend continuously; and octopus arms and plant tendrils combine bending, twisting, and

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coiling. Building on these, Zhou et al. categorized bio-inspired soft grippers by impactive motion into discontinuous bending, continuous bending, and continuous twisting, linking biological mechanisms directly to engineered structure [2].

Research has evolved from early designs to smart materials, variable-stiffness mechanisms, additive manufacturing, flexible sensing, and data-driven control. While compliance ensures safe geometric adaptation, excessive softness compromises load capacity and grasp stability. Similarly, high-degrees-of-freedom deformation improves adaptability but hinders state estimation and precise control. Thus, the core design challenge is not maximizing softness but balancing compliant contact, stable support, actuation speed, and controllability.

Against this background, this review addresses three questions: First, how are biological grasping morphologies and motion mechanisms translated into soft-gripper structures? Second, how do actuation, material selection, and stiffness regulation affect compliance, load capacity, and grasp stability? Third, what limitations remain in practical applications, and which directions are likely to shape further development?

2. Structural design and grasping mechanisms of bio-inspired soft grippers

2.1. Biological basis and engineering translation of bio-inspired grasping

Biological organisms have evolved a wide range of grasping structures in response to different environments. Unlike conventional mechanical grippers, which rely on rigid joints to execute prescribed motions, many biological grasping behaviors arise from the combined effects of morphology, material compliance, and passive deformation after contact. Bio-inspired soft gripper design therefore aims not to reproduce biological appearance literally but to extract motion and contact principles that can be implemented in engineered structures.

In terms of kinematic continuity, the human hand and bird foot contain distinct skeletal segments and joints, allowing local joint rotations to modify endpoint posture. By contrast, flexible structures such as plant tendrils and octopus arms exhibit continuous bending, twisting, and winding. Zhou et al. accordingly classified bio-inspired soft grippers into three categories: discontinuous bending, continuous bending, and continuous twisting [2]. This scheme shifts the emphasis from the biological organism itself to the engineering form of motion, avoiding a purely taxonomic description based on examples such as hands, octopus arms, or plants.

2.2. Bio-inspired grippers with discontinuous bending

Discontinuous-bending grippers typically contain finger- or phalanx-like elements inspired by biological end effectors with skeletal-joint architectures, such as human hands and bird feet. Such grippers need not be entirely soft. Flexible joints and compliant materials can be combined with local support elements to form hybrid rigid-soft structures. Compared with fully continuous bodies, their deformation is spatially more localized, which generally makes actuation and control relationships easier to establish.

Underactuation is particularly representative in hand-inspired designs. Hassan et al. combined human-hand geometry, tendon-like cable actuation, and soft materials to develop a low-cost, underactuated soft gripper with passive adaptability, and they compared the effects of different materials on grasping and holding performance [3]. By reducing the number of independently driven elements, multiple compliant phalanges can adjust their posture through material deformation and residual mechanical degrees of freedom after contacting an object, allowing the gripper to adapt to objects of different shapes.

Discontinuous-bending structures illustrate the role of morphology in control. Some geometric matching that would otherwise require sensing and feedback can be achieved passively through compliant deformation

at contact. Shintake et al. described this as morphological computation, whereby material compliance itself helps reduce control complexity [1].

2.3. Bio-inspired grippers with continuous bending

Continuous-bending grippers have no distinct rigid revolute joints. Their curvature is generated by elastomeric bodies, soft chambers, fiber-reinforced constraints, or continuous compliant backbones. Because deformation can extend over a relatively large region, these grippers can create broad contact areas when handling spherical, irregular, or delicate objects.

Pneumatically actuated soft fingers are common examples. Air chambers embedded in an elastomer are designed to undergo unequal extension, so pressurization produces asymmetric deformation and, consequently, bending. In the pressure-driven grippers reviewed by Zhou et al., chamber geometry, constraint layers, and modular architecture were used to tune bending behavior, while some designs employed dual chambers to achieve bidirectional bending [2].

The Fin Ray effect is another biological principle used in continuously deformable fingers. Xin et al. noted that a Fin Ray structure consists of a flexible outer frame connected by internal ribs. Contact with an object produces coupled deformation within the structure, causing the gripping surface to conform to the object's contour and enabling passive adaptive grasping [4].

Continuous-bending structures are highly adaptable and can provide gentle contact, but their kinematics and mechanics are strongly nonlinear. Material properties, actuation pressure, wall thickness, chamber geometry, and contact location can all influence the final configuration and grasping behavior. Structural design therefore needs to be considered together with actuation and control rather than treated in isolation.

2.4. Bio-inspired grippers with continuous twisting and wrapping

Compared with simple bending, octopus arms, plant tendrils, and snake bodies exhibit more complex three-dimensional continuous motions. Elongation, bending, and twisting can be combined to envelop or wind around an object, distributing grasping forces over a larger contact region.

To address the limited grasping force of conventional multi-finger soft grippers and the relatively limited study of spiral wrapping deformation, Cao et al. developed a fiber-reinforced, closed bio-inspired spiral-wrapping soft gripper. The design forms a closed grasp by helical winding of its actuator, and the authors analyzed its deformation and grasping characteristics through theoretical modeling, simulation, and experiments. Their experiments indicated that the closed wrapping mode provided favorable object adaptability and load-bearing capability [5].

Wrapping can improve stability relative to conventional two- or three-finger pinching by increasing the contact area, but it also requires additional operating space. Shan et al. noted that fully enveloping or continuum-wrapping architectures typically offer good stability and load-bearing performance; however, allowing the object to enter the gripper and completing the wrapping motion generally demands sufficient workspace, which constrains their use in confined or cluttered environments [6].

3. Actuation, materials, and stiffness regulation in bio-inspired soft grippers

3.1. Representative actuation methods and their characteristics

Actuation strongly influences the architecture, response speed, output capability, and control strategy of a soft gripper. Shan et al. grouped common soft actuation approaches into field-driven, fluidic, and cable-driven

methods [6]. In practical soft-gripper designs, pneumatic actuation, tendon or cable actuation, and smart-material actuation are among the most widely used implementations.

Pneumatic and low-pressure hydraulic systems deform compliant chambers by changing their internal pressure. Their simple structure, low mass, and safe contact characteristics have led to widespread use in soft grippers. Nevertheless, gas compressibility and the intrinsic nonlinearity of soft materials make precise control more difficult, and pneumatic systems typically require pumps, valves, and pressure regulators. AboZaid et al. noted that external pumps and compressors hinder miniaturization and portability, while flow-path resistance can also limit response speed [7].

Tendon-driven designs use motors to generate tensile forces that are transmitted to compliant fingers through cables or tendons. Compared with purely pneumatic systems, tendon actuation provides a more explicit force-transmission path and can facilitate higher output forces. It nevertheless introduces practical issues such as cable routing, friction, wear, and the integration of rigid actuators with soft structures.

Smart-material actuators exploit material deformation or changes in physical properties. Examples include shape-memory alloys, shape-memory polymers, electroactive materials, and magnetically or optically responsive materials. By reducing the need for conventional transmission mechanisms, these approaches can support compact designs and, in some cases, remote or contactless actuation. Their performance, however, varies substantially in response time, force output, cycling stability, and operating requirements. Thermally activated materials, for example, may require both heating and cooling stages, which limits rapid cyclic operation [2, 6].

No single actuation method is optimal for every application. Pneumatic systems favor compliance and large deformation; tendon-driven systems offer advantages in force transmission and controllability; and smart materials provide opportunities for miniaturized or unconventional architectures. Selection must therefore be made in relation to object size, required grasping force, response speed, and the operating environment.

3.2. Soft materials and additive manufacturing technologies

Material selection in a soft gripper governs both load-bearing capability and deformation. Common choices include silicone elastomers, thermoplastic polyurethane, UV-curable elastomers, hydrogels, and functional composites. Unlike materials in conventional rigid mechanisms, these materials are not merely passive structural media: elastic modulus, extensibility, frictional behavior, and stimulus responsiveness can all contribute directly to motion and grasping.

Advances in additive manufacturing have also changed how soft grippers are fabricated. Xin et al. classified relevant 3D-printing approaches into extrusion-, jetting-, and photopolymerization-based processes, including FDM, DIW, PolyJet, SLA, and DLP, and discussed their use with both functional and non-functional materials as well as in grippers with integrated sensors [4].

Beyond shortening prototyping cycles, 3D printing can realize complex internal channels, thin-walled geometries, graded multi-material structures, and embedded compliant mechanisms that are difficult to produce with conventional molding. Xin et al. further pointed out that additive manufacturing can enable direct sensor integration, creating a route from simple structural fabrication toward integrated fabrication of structure, function, and sensing [4].

Each printing process, however, remains constrained by material compatibility, resolution, equipment cost, and multi-material processing. Further progress therefore depends on better compatibility between soft and functional materials and on high-precision multi-material fabrication capable of supporting complex structures, soft actuation, and embedded sensing.

3.3. Variable stiffness and rigid-soft coupled design

Compliance is central to safe, adaptive contact, yet insufficient stiffness can reduce gripping force and operational stability. Zhou et al. noted that low-stiffness states facilitate adaptive enveloping, whereas an increase in structural stiffness can improve holding force and load-bearing capacity [2]. Variable-stiffness mechanisms have therefore become an important means of addressing the tension between compliance and load capacity. Existing approaches can be broadly grouped into structural reconfiguration, modulation of material properties, and jamming based on particles or layers [6]. Jamming changes the constraint between granular or laminar elements to switch between soft and stiff states. Although conceptually straightforward, such mechanisms may require a vacuum source and can face challenges in weight, miniaturization, and attainable stiffness range. Material-based approaches use low-melting-point materials, shape-memory polymers (SMPs), or other field-responsive materials to alter stiffness, but response time and thermal management must often be considered.

From this perspective, future bio-inspired soft grippers are unlikely to benefit from making every component uniformly softer. A more useful strategy is rigid-soft coordination in which the gripper remains compliant during contact and becomes mechanically reinforced during load support. The design objective is thus shifting from static material softness toward task-dependent regulation of mechanical properties.

4. Applications of bio-inspired soft grippers

Table 1 compares representative application domains and highlights the performance requirements that differ across them. All four application domains require geometric conformity and low-damage contact, but the dominant engineering constraints differ. Industrial and food-handling applications emphasize cycle time, cleanability, maintenance, and cost; agricultural harvesting is more strongly affected by unstructured environments and variability among objects; and medical, human-robot, and underwater applications impose particularly demanding requirements on safety, reliability, and sensing [2, 7].

Table 1. Representative application scenarios and key requirements for bio-inspired soft grippers [2, 7]

Application scenario	Representative objects	Principal advantages	Main challenges
Industrial and food handling	Multi-variety workpieces; deformable or fragile foods	Compliance; large contact area; reduced damage	Cycle time, cleanability; cost
Agricultural harvesting	Apples, citrus, kiwifruit, tomatoes	Passive conformity; reduced bruising and scratching	Perception; foliage interference; ripeness variation; reliability
Medical and human-robot interaction	Fragile objects; human-robot contact tasks	Impact buffering; reduced contact pressure	Safety; sensing accuracy; reliability
Underwater and special environments	Jellyfish and other delicate aquatic specimens	Low stiffness; gentle handling	Environmental adaptability; material durability; sensing; reliability

4.1. Flexible grasping in industrial and food handling

Flexible manufacturing increasingly requires a single robotic system to handle products that vary in size, shape, and surface properties. Conventional fixtures are often tailored to specific objects, whereas soft grippers can accommodate such variation through structural compliance. In their review of industrial and food-handling

applications, AboZaid et al. highlighted the adaptability of soft structures when handling foods that deform easily or are susceptible to damage [7].

Food handling is a particularly clear example of this advantage. Food items often vary substantially in shape, have wet or slippery surfaces, and possess low mechanical strength, so excessive local gripping force can cause damage. By spreading the applied force over a larger contact area, soft grippers can reduce local pressure and the associated risk of damage when the gripping force is properly controlled. Industrial deployment, however, also depends on cycle time, cleanability, service life, system cost, and control reliability. AboZaid et al. identified control performance and cost among the factors that continue to limit broader commercialization [7].

4.2. Agricultural harvesting and manipulation of delicate objects

Agriculture is one of the most representative application areas for bio-inspired soft grippers. Fruits and vegetables vary in size, shape, ripeness, and surface mechanical properties, while leaves and branches frequently obstruct access to the target. An end effector must therefore grasp reliably while minimizing bruising and surface damage.

Continuously bending soft fingers and passive adaptive structures based on the Fin Ray effect are well suited to such tasks. After contact, the compliant structure redistributes the contact region according to the object's geometry without requiring exact prior knowledge of its shape. Reviews have reported soft-gripper applications involving berries, apples, citrus fruit, kiwifruit, and tomatoes [7].

Successful agricultural harvesting cannot be judged solely by whether an object can be grasped. Field deployment must also account for perception error, interference from foliage and branches, changes in material properties with ripeness, post-grasp detachment, and reliability over repeated cycles. These requirements are driving agricultural soft grippers beyond purely mechanical adaptation toward closed-loop operation that combines vision, tactile sensing, and force feedback.

4.3. Medical, human-robot, and special-environment manipulation

The intrinsic compliance of soft grippers is attractive in medical manipulation, human-robot interaction, and other tasks that demand low-damage contact, high safety, or operation in complex environments. Compared with rigid end effectors, compliant materials can attenuate impacts during accidental collisions and distribute contact forces over a wider area.

Underwater manipulation further illustrates the value of compliant grasping in demanding environments. Zhou et al. reviewed examples in which low-stiffness soft fingers were used to handle fragile aquatic organisms such as jellyfish, as well as transparent hydrogel grippers designed for underwater grasping. In both cases, the common objective was to reduce mechanical damage to delicate specimens [2]. These examples show that the purpose of bio-inspired soft grasping is expanding from simply securing an object to achieving safe, adaptive, and sensing-enabled physical interaction.

At the same time, medical, underwater, and human-robot applications impose stricter requirements on reliability, material durability, sensing accuracy, and system safety, making engineering deployment considerably more demanding.

5. Challenges and future directions for bio-inspired soft grippers

5.1. Trade-offs among compliance, load capacity, and grasp stability

Existing studies have shown that compliant structures can markedly improve geometric adaptability to irregular objects, but compliance alone does not determine overall grasp performance. Lower structural stiffness generally favors passive adaptation, yet it can also lead to excessive deformation under external loads and thereby reduce pose retention and manipulation accuracy. Conversely, adding rigid reinforcement can improve stability at the expense of conformity to object surfaces.

Accordingly, the central design question is shifting from how to create compliance to how to regulate it. Shan et al. noted clear trade-offs among flexibility, stability, and load capacity for different contact modes and further observed that a single variable-stiffness principle rarely achieves a large stiffness range, rapid response, low weight, and miniaturization simultaneously [6].

Future designs will therefore need to combine multi-material architectures, rigid-soft coupling, local stiffness regulation, and possibly multiple stiffening mechanisms so that a gripper can remain compliant during contact yet provide adequate stiffness during stable holding and subsequent manipulation.

5.2. Multimodal sensing and closed-loop grasp control

Passive deformation can reduce the control burden of a soft structure, but mechanical compliance alone is insufficient for stable manipulation, slip detection, or precise force regulation. In their review of tactile sensing for soft grippers, Qu et al. covered capacitive, piezoresistive, piezoelectric, fiber Bragg grating, vision-based tactile, and triboelectric sensing and identified force measurement, object-property perception, slip detection, and multimodal information fusion as important application areas [8].

Integrating flexible sensors into soft structures remains difficult. A sensor must deform with the gripper without substantially altering its native compliance, and it must retain stable performance under repeated large strains. For this reason, softness in future grippers will need to extend beyond the actuator and body structure to the sensing system itself.

5.3. Integrated structure-actuation-sensing design and intelligent grasping

With advances in machine learning and robotic perception, soft grasping is evolving from passive conformity toward autonomous sensing and active adjustment. Majumder et al. presented a learning-based soft-grasping framework that spans soft-gripper design and multimodal sensing through grasp planning, control, and generalization [9].

Because soft grippers deform continuously, possess many degrees of freedom, and exhibit hysteresis and material nonlinearities, their state is more difficult to describe than that of rigid manipulators using only joint angles and motor positions. This makes data-driven methods attractive, but it also introduces challenges such as large training-data requirements, simulation-to-reality discrepancies, and limited model transferability across different gripper designs [9].

Recent studies have explored autonomous soft robotic systems with multimodal sensing and adaptive manipulation, deep-learning-based grasping with soft enveloping grippers, and reinforcement-learning strategies for variable-stiffness grasping [9-11]. Collectively, these efforts suggest a shift away from designing the mechanical structure, sensing hardware, and control algorithm as separate subsystems toward a coordinated structure-material-actuation-sensing-control architecture.

Majumder et al. further identified the integration of physics-based models with data-driven strategies, self-supervised learning, sim-to-real transfer, and end-to-end multimodal perception and control as promising

directions [9]. On this basis, bio-inspired soft grippers may extend beyond morphological and motion-level biomimicry toward perception-decision-action loops that more closely resemble those of biological systems.

6. Conclusion

Bio-inspired soft grippers draw on biological structures and motion patterns used for grasping, enveloping, and winding, offering alternative strategies for handling soft, fragile, and geometrically irregular objects that challenge conventional rigid grippers. Current designs span discontinuous bending, continuous bending, and continuous twisting or wrapping. Finger-like architectures provide relatively explicit actuation relationships; continuous compliant structures offer strong geometric adaptability; and wrapping or enveloping architectures can improve grasp stability by increasing contact area.

From an engineering perspective, pneumatic, tendon-driven, and smart-material actuation each offer distinct advantages, while developments in materials and 3D printing have expanded the range of complex compliant and multi-material structures that can be fabricated. At the same time, compliance is itself a limitation when stiffness becomes too low to support load or maintain a stable grasp. Variable-stiffness and rigid-soft coupled designs have therefore emerged as important approaches for reconciling compliant contact with stable load bearing.

Bio-inspired soft grippers have been investigated for food handling, agricultural harvesting, human-robot interaction, medical manipulation, and underwater specimen handling. Moving from laboratory prototypes to long-term engineering deployment, however, requires further improvements in material fatigue resistance, actuator integration, accurate state sensing, control stability, and system cost.

Overall, the research focus is moving away from simply reproducing biological morphology or maximizing material softness and toward coordinated design of structure, materials, actuation, stiffness, sensing, and control. Multimodal flexible sensing, dynamic stiffness regulation, additive manufacturing, and the combination of physics-based models with data-driven control may further improve adaptability to unfamiliar objects and unstructured environments. For bio-inspired soft grippers to achieve practical engineering relevance, they must ultimately do more than grasp gently: they need to sense contact conditions, interpret them, and adjust the grasping strategy accordingly.

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