# Exploring Actuation Strategies in Soft Robotics

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Abstract: Soft robots are increasingly attracting attention due to their flexibility, safety, and high adaptability in complex environments. Since drive technology plays an extremely important core role in determining the performance and functionality of soft robots, conducting a systematic review of existing drive technologies is crucial for advancing this field. This paper provides an overview of the four major categories of soft robot drive technologies: pneumatic-hydraulic drives, electromagnetic drives, chemical drives, and hybrid drive systems. For each category, this paper analyzes representative studies to summarize their working principles, application scenarios, and performance characteristics. By comparing these drive technologies across metrics such as energy efficiency, controllability, and integration potential, the paper identifies their respective advantages and limitations. This paper aims to provide engineers and researchers developing high-performance soft robots with a comprehensive reference on drive technologies and highlights potential future research directions in areas such as material innovation, multimodal control, and system integration.

## 1 INTRODUCTION

In recent years, with the rapid development of bionic engineering, flexible materials science, and intelligent control technologies, soft robots have emerged as a prominent research focus in the field of robotics. Compared with traditional rigid robots, soft robots are primarily inspired by nature and are characterized by functional diversity, high adaptability, and the ability to perform multiple complex tasks simultaneously (Yasa et al., 2023). They exhibit broad application prospects in areas such as biomedicine, wearable devices, and operations in complex environments.

The initial development of soft robots largely relied on traditional actuation methods such as pneumatic and hydraulic systems, with structural designs often inspired by biological organisms like octopuses and worms (Kim, Laschi, & Trimmer, 2013). In recent years, researchers have begun exploring hybrid actuation systems that integrate magnetic, electrical, and chemical stimulus-responsive mechanisms, aiming to achieve higher degrees of freedom and more precisely controllable soft actuation (Ebrahimi et al., 2021). Constructed primarily from flexible materials that mimic the properties of soft-bodied organisms, soft robots are capable of navigating freely through dynamic, confined, and irregular environments (Wang et al., 2024). As one of the core technologies enabling the functionality of soft robots, actuation methods directly determine their locomotion patterns, load-bearing capacity, operational precision, and response speed, and thus play a critical role in enhancing overall robotic performance. The effectiveness of an actuation strategy not only influences the fundamental capabilities of soft robots but also directly impacts their applicability in the real world. For instance, in medical catheters or minimally invasive surgical instruments, actuation systems must be compact, highly controllable, and durable (Cianchetti et al., 2018). Current mainstream actuation methods include pneumatic, hydraulic, and magnetic actuation. However, they still face several challenges in terms of controllability, energy efficiency, and system stability. These limitations become even more pronounced in the face of emerging requirements such as actuation within highly flexible materials, power delivery for wearable systems, and the miniaturization of soft robots. As a result, the development of diverse and high-performance actuation strategies has become a focal point of research in the field (Walker et al., 2020).

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Although several recent reviews have focused on specific actuation technologies within the field, there remains a lack of systematic cross-comparative and integrative analyses of diverse actuation principles. This paper aims to provide a comprehensive review of current mainstream actuation methods for soft robots from the following perspectives: gas/liquid-based actuation, electromagnetic/magnetic actuation, chemically driven actuation, and the development of emerging actuation techniques. By systematically outlining the research landscape and identifying the current challenges in soft robotic actuation, this review seeks to offer theoretical guidance for future research and development in soft robotic actuation systems.

# 2 PNEUMATIC AND HYDRAULIC ACTUATION IN SOFT ROBOTICS

Pneumatic and hydraulic actuation are among the earliest and most widely applied methods in soft robotic systems. These approaches rely on the injection or withdrawal of gas or liquid into a sealed flexible chamber to induce internal pressure changes, which in turn lead to structural deformation and enable specific movement functions. This actuation mechanism closely resembles the behavior of soft-bodied organisms in nature, such as octopuses and worms, and is therefore commonly used in the design of bioinspired soft structures.

## 2.1 Pneumatic Actuation Application

One representative example is the McKibben pneumatic actuator (MPA), a type of soft artificial muscle composed of a rubber bladder encased in a braided mesh sleeve. When compressed air is pumped into the bladder, it contracts in length and expands in diameter, mimicking the contraction behavior of biological muscles. Researchers have enhanced the functionality of MPAs by applying elastic adhesive coatings to enable bending motion, and based on this design, they have developed multi-segmented soft robotic arms capable of performing tasks such as object grasping and fine manipulation (Kan et al., 2025).

Bertrand Tondu et al. developed a static model of the basic McKibben muscle based on three key parameters: the initial braid angle, the initial muscle length, and the initial muscle radius. The model also incorporates a three-parameter friction model for the muscle fiber itself, and has been shown to perform effectively under both isometric and isotonic contraction conditions (Tondu & Lopez, 2002).

This type of actuation features a simple structure that is easy to manufacture and maintain. By mimicking the contraction behavior of biological muscles, it offers good compliance and biomimetic performance, along with a high actuation force capable of supporting heavy loads. However, it suffers from limited control precision due to sensitivity to pressure fluctuations. Additionally, both inflation and deflation processes require time, resulting in relatively slow response speeds and making it difficult to achieve high-frequency motions.

## 2.2 Hydraulic Actuation Application

Hydraulic actuation, which operates on principles similar to pneumatic systems, utilizes incompressible fluids to deliver higher output forces, making it suitable for applications requiring strong load-bearing capabilities. Qinlin Tan et al. proposed the use of rigid structural components to strategically reinforce otherwise omnidirectionally flexible soft actuators, significantly improving their load capacity and actuation precision. Their hybrid soft-rigid multi-joint leg design features quasi-linear motion and force characteristics while preserving excellent passive impact compliance through the inherent flexibility of soft actuators. The team also developed a novel valveless hydraulic actuation system incorporating a peristaltic pump, enabling a compact, lightweight, and untethered underwater crawling robot prototype. The robot demonstrated a payload-to-weight ratio of 5:1 and supported multiple gait modes (Tan et al., 2021).

This actuation structure provides a strong driving force, making it suitable for complex terrains and heavy-load scenarios. It enables smoother and more stable motion and offers higher precision in propulsion control. The system also exhibits overall good compliance and low material cost. However, hydraulic systems are mechanically complex, requiring precise pump control and effective sealing, and they are prone to fluid leakage, demanding high standards of system stability and reliability.

## 2.3 Analysis of Advantages and Disadvantages

Due to their high actuation force and flexibility, pneumatic and hydraulic systems have played a crucial role in the field of soft robotics, particularly in task-oriented systems such as soft arms, grippers, and mobile platforms. Nevertheless, these actuation methods typically rely on external equipment (e.g., compressors or air pumps), resulting in high system complexity and slow response speeds. Such limitations hinder their applicability in future-oriented scenarios that require portability, wearability, or miniaturization. As a result, although fluidic actuators currently dominate applications in soft robotics, their development is gradually shifting toward system integration, intelligent control, and material optimization.

# 3 ELECTROMAGNETIC ACTUATION IN SOFT ROBOTICS

Electromagnetic actuation refers to the use of electric fields, magnetic fields, or electro-thermal energy conversion to induce physical deformation in actuator materials, thereby enabling motion in soft robots. This category of actuators typically does not require bulky external pump systems, offering advantages such as compact structure and fast response speed. As a result, electromagnetic actuation has attracted significant attention in applications involving miniaturization, wearability, and bioinspired robotics.

Dielectric elastomers, which are electrostatically actuated by applying voltage across compliant electrodes and dielectric polymers, represent a prominent class of actuators in this domain. Owing to their lightweight, geometric flexibility, cost-effectiveness, and rapid response, dielectric elastomer actuators (DEAs) can be configured into a variety of shapes, making them highly promising for artificial muscle-like actuation. To date, soft actuators such as electroactive polymer actuators, shape memory alloy actuators, shape memory polymer actuators, and fluidic actuators (hydraulic or pneumatic) have opened up numerous possibilities in areas such as artificial muscles, biomimetic robotics, and human–machine interfaces (Youn et al., 2020).

## 3.1 Application

In 2020, Christoph Keplinger proposed a novel circuit design that eliminates the need for any high-voltage sensing components, thereby enabling the use of off-the-shelf components to create simple and cost-effective circuits. This design enabled the synchronized sensing and actuation of a range of electrostatic transducers, achieving precise displacement estimation with an error margin of less than 4%. Furthermore, the circuit was developed into a compact and portable system that integrates high-voltage actuation, sensing, and computation, serving as a prototype for wireless, multifunctional soft robotic systems (Ly et al., 2021).

Magnetic-responsive actuation typically involves embedding trace amounts of magnetic particles into elastomeric materials, allowing the structure to deform or move under the influence of an external magnetic field. Dan Liu et al. developed a magnetically actuated soft continuum microrobot for intravascular microsurgery, which demonstrated capabilities in both steering and locomotion. The soft continuum microrobot was fabricated from a composite of neodymium–iron–boron (NdFeB) particles and polydimethylsiloxane (PDMS), with diameters as small as 200 μm. Moreover, the robot's surface was coated with a hydrogel layer that not only mitigated the adhesive forces between the miniature components and the soft tip, but also reduced friction between the robot and the substrate. The resulting system is wirelessly operated and remotely controllable, making it well-suited for tasks in complex or confined environments, such as in medical applications (Liu et al., 2022).

## 3.2 Analysis of Advantages and Disadvantages

Overall, electromagnetically actuated soft robots offer the advantage of remote control, enhancing system deployment flexibility. Their structural simplicity and actuation precision—determined by magnetic field strength and particle distribution—make them well-suited for miniature soft robotic designs, particularly in applications requiring compactness, high precision, or wearability. Compared to pneumatic or hydraulic systems, they do not require external pump sources, facilitating integration and lightweight system design. However, such robots typically generate relatively low actuation forces, which limits their applicability. Furthermore, the need for uniform magnetic materials and highly precise magnetic field control systems often results in high manufacturing costs.

# 4 CHEMICAL ACTUATION IN SOFT ROBOTICS

Chemical actuation induces deformation or motion in soft structures by releasing gases, heat, or other forms of physical energy through chemical reactions. Without relying on external power sources or pump systems, this type of actuation can achieve a certain degree of "autonomous response." Kousuke Moriyama et al. employed an enzymatic reaction as the power source for soft robots, utilizing oxygen ($O_2$) gas generated from the catalyzed decomposition of hydrogen peroxide ($H_2O_2$) by the widely available enzyme catalase to drive a pneumatic soft robot. The generation of $O_2$ gas was influenced by the concentration of catalase, the concentration of $H_2O_2$, and the supply rate of $H_2O_2$. The study demonstrated that catalase-catalyzed reactions can serve as an effective power source for soft robotic systems, highlighting a novel application prospect for enzymatic processes. Moreover, enzymatic reactions occur under mild conditions, reducing the risk of overheating or damage to robotic components and materials. These reactions also offer high biocompatibility, and their byproducts are typically non-toxic, enhancing safety during both operation and disposal (Moriyama et al., 2024).

## 4.1 Application

In 2013, Dr. Robert F. Shepherd and colleagues achieved rapid actuation of a soft robot using a high-temperature chemical reaction. A computer-controlled electric spark ignited a premixed combination of methane and oxygen within the robot, triggering combustion that pressurized the robot's pneumatic channels and enabled it to jump. The heat generated by the explosion dissipated quickly, allowing repeated jumps without damaging the robot. This actuation approach offers self-contained mobility without the need for external power sources or controllers. Due to the high efficiency of chemical reactions and their large instantaneous energy release, this method demonstrates strong potential for high-power, untethered soft robotic systems (Shepherd et al., 2013).

## 4.2 Analysis of Advantages and Disadvantages

Chemical actuation methods, characterized by the absence of external equipment, structural simplicity, and ease of deployment, are particularly well-suited for single-use tasks in field environments, disaster zones, and microscale settings. However, their limited controllability, irreversibility of actuation reactions, low repeatability, and high sensitivity to environmental conditions pose significant challenges. These factors hinder their broader adoption in soft robotic systems that require high stability and precision.

# 5 EMERGING HYBRID ACTUATION STRATEGIES IN SOFT ROBOTICS

As the limitations of traditional actuation methods—such as pneumatic, electromagnetic, and chemical systems—in terms of controllability, miniaturization, and environmental adaptability become increasingly apparent, researchers have begun exploring hybrid actuation strategies that couple two or more mechanisms. These emerging hybrid systems often integrate different forms of energy input to achieve multi-degree-of-freedom motion, high responsiveness, and improved energy efficiency in soft robotic actuation.

## 5.1 Application

Seyed M. Mirvakili et al. developed a simple mechanism and design for actuating pneumatic artificial muscles and soft robotic grippers without relying on compressors, valves, or pressurized gas tanks. Their actuation approach leverages magnetically susceptible fluids undergoing a liquid–gas phase transition, which generates internal pressure within the artificial muscle. The volume expansion during the phase transition creates sufficient force to perform mechanical operations. This actuation mechanism was integrated into both McKibben-type artificial muscles and soft robotic arms. The untethered McKibben artificial muscle achieved up to 20% actuation strain within 10 seconds, with an energy density of 40 kJ/m$^3$—exceeding the peak strain and energy density of skeletal muscle. The untethered soft robotic arm, powered solely by two lithium-ion batteries, demonstrated the capability to lift objects effectively (Mirvakili et al., 2020).

## 5.2 Analysis of Advantages and Disadvantages

Biohybrid soft robots integrate living cells or biological tissues with artificial flexible structures, achieving actuation and motion through spontaneous cellular contractions or electrochemical stimulation. These robotic systems exhibit a high degree of biomimicry, possessing capabilities such as self-healing, environmental adaptability, and a certain level of autonomy. While most conventional actuators rely on external power sources, biohybrid actuators can harvest energy directly from their surroundings, enabling the design of untethered systems without the need for bulky battery packs.

The ability of biohybrid actuators to adapt to mechanical loads and self-repair makes robotic devices more resilient to damage and capable of regaining function after failure. Furthermore, the capacity to recruit additional muscle fibers to modulate actuator strength allows for force control within compact system architectures. By leveraging these capabilities, biohybrid robots at the macroscale will be able to safely interact with various biological organisms, adapt to mechanical stresses and environmental conditions, and sustain themselves through energy harvested directly from their environment (Won et al., 2020).

# 6 NOVEL HYBRID ACTUATION

Novel hybrid actuation strategies overcome the physical limitations of conventional mechanisms by integrating multimodal energy conversion processes, demonstrating significant advantages in biomimicry, energy efficiency, and structural compactness. These systems show great promise in cutting-edge applications requiring untethered operation, remote control, and adaptability to microscale environments. However, their practical deployment still faces considerable challenges. Current hybrid actuators generally exhibit low technological maturity and high manufacturing costs, while issues such as control precision, response stability, and system longevity remain in need of substantial improvement. Therefore, despite their considerable potential, hybrid actuation systems are presently focused on fundamental research and prototype validation. Their transition toward practical implementation will require advances in novel materials, interdisciplinary collaboration, and systematic optimization of integration strategies.

# 7 RESEARCH BOTTLENECKS AND FUTURE DEVELOPMENT TRENDS

With the continued advancement of soft robotics research, the diversity and functional complexity of actuation systems have significantly increased. However, transitioning from laboratory prototypes to real-world applications still faces a series of common technical bottlenecks. At the same time, emerging technological innovations provide directional insights for future developments in actuation systems.

## 7.1 Common Bottlenecks

First is response speed and latency issues. Certain actuation methods, such as pneumatic/hydraulic systems, shape memory alloys (SMAs), and chemical actuators, suffer from slow response times and low cycle efficiency, making them unsuitable for high-frequency control or rapid movements. This limitation is particularly critical in miniaturized devices and medical scenarios, where actuation speed is a key determinant of usability.

Second is high integration complexity. Most current actuators still rely on external gas sources, hydraulic pumps, power supplies, or magnetic coils, resulting in bulky system designs and complex control architectures. In multimodal actuation systems, the diversity of actuation mechanisms, energy requirements, and control logic across different modules leads to significant integration challenges. Achieving centralized power supply and unified control of multiple modes remains a major engineering obstacle in actuation system development.

## 7.2 Future Perspectives

Future advances are expected in the development of novel actuation materials that exhibit high flexibility, strength, and self-healing capabilities. Breakthroughs in deformable metals, conductive elastomers, and liquid metals may provide essential material foundations for constructing high-performance, high-strength soft actuation systems. The integration of artificial intelligence for intelligent control of multimodal actuation systems will be crucial for managing complex tasks. Through machine learning and data fusion algorithms, real-time feedback, predictive control, and energy management across multiple actuators can be realized, improving the overall system's responsiveness and coordination.

In addition, advanced manufacturing techniques will play an important role in microstructural fabrication and functional material printing for actuators. Specifically, multi-material 3D printing and rapid photopolymerization techniques will support the construction of highly integrated and complex actuation components, enabling a transition from manual assembly to functionally integrated structural manufacturing in soft robotics.

# 8 CONCLUSIONS

This paper systematically explores the drive mechanisms in the field of soft robotics from four perspectives: pneumatic-hydraulic drive, electromagnetic drive, chemical drive, and emerging hybrid drive mechanisms. By analyzing representative studies within each category, this paper compares and contrasts the intrinsic implementation mechanisms, adaptability, and performance of these driving mechanisms.

Pneumatic-hydraulic drive systems excel in high-stress output performance, enabling them to carry heavier loads. However, they still suffer from the drawbacks of bulky external components and limited operational speed. Electromagnetic drive systems demonstrate faster response times and greater integration potential but are constrained by output strength and energy requirements. Chemical drive systems offer advantages such as integration, compact size, and self-sufficiency but struggle with precise control and lack repeatability. Hybrid drive systems can combine multiple drive systems to achieve multifunctionality, wireless control, and adaptive soft robotics, but most hybrid soft robots are still in the experimental stage and have not yet been mass-produced.

This paper highlights the key challenges in the development of soft robotics through classification and comparative analysis, including energy efficiency, system integration challenges, and control precision. This review emphasizes the importance of interdisciplinary collaboration, encompassing materials science, control engineering, and biomimetic design, to drive the transition of soft robots from laboratory prototypes to practical applications.

This review provides a theoretical foundation and reference for future research on high-performance, intelligent soft robot systems and may guide the development of soft robots for biomedical applications, wearable devices, and complex environments.

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