

# Liquid Crystal Elastomers as Actuators for Soft Robotics: A Review

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## ABSTRACT

Soft robotics relies on materials that are lightweight, flexible, and capable of large, reversible shape changes. Liquid crystal elastomers (LCEs) have become a leading candidate because they couple the orientational order of liquid crystals with the elasticity of polymer networks, enabling programmable deformation under thermal, optical, magnetic, or chemical stimuli. Over the past decade, advances in synthesis and processing have transformed LCEs from laboratory curiosities into increasingly practical actuator materials. This review surveys key developments from 2015 to 2025, highlighting progress in fabrication methods, actuation strategies, and emerging robotic applications. Techniques such as controlled crosslinking, additive manufacturing, fiber-based architectures, and field-guided alignment now allow precise control over molecular orientation and actuator geometry. Recent innovations have improved mechanical robustness, responsiveness, and integration with multifunctional components, though challenges remain in achieving rapid actuation and scalable manufacturing. Overall, LCEs are evolving into a versatile platform for adaptive, high-performance soft robotic systems, with continued advances in materials design and system-level integration poised to expand their capabilities further.

## INTRODUCTION

Soft robotics has emerged as a rapidly advancing field, aiming to create machines that are compliant, adaptive, and capable of safe interaction with humans and unstructured environments. Unlike traditional rigid robots, soft robotic systems use materials that can bend, stretch, and reconfigure in response to external stimuli, enabling novel forms of locomotion, manipulation, and biomedical applications (Jiang et al., 2024).

A key challenge in soft robotics is the development of artificial muscles, materials that convert energy inputs into reversible motion with sufficient strain, stress, and speed. Several smart material platforms have been investigated, including pneumatic actuators, hydrogels, shape memory alloys (SMAs), and dielectric elastomers (DEAs). However, each of these faces limitations in scalability, efficiency, or cycle life (Ince et al., 2024).

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Liquid crystal elastomers (LCEs) have recently gained attention as a promising solution. Built from aligned mesogenic networks within a soft polymer, LCEs exhibit reversible actuation in response to thermal, optical, or magnetic stimuli. In recent years, significant progress has expanded the performance and practicality of LCE systems. For example, chain-entanglement reinforcement has improved mechanical toughness without sacrificing actuation strain (Agrawal et al., 2025), addressing historical concerns about durability. Hierarchical bundled fiber architectures with integrated cooling mechanisms have improved thermal dissipation and increased actuation frequency (Sepehri et al., 2025). Advances in tunable interfacial adhesion have further enabled adaptive grippers capable of conforming to irregular surfaces while maintaining strong contact (Annapooranan et al., 2024). Together, these developments suggest that LCEs are transitioning from laboratory materials toward viable soft robotic components.

This review examines major advancements in LCE research from 2015 through 2025, with emphasis on fabrication strategies, actuation mechanisms, and representative soft robotic applications. One foundational work (Warner & Terentjev, 2007) published before this period is cited to establish core concepts. The literature search began with a focused examination of recent publications from Professor Shengqiang Cai's group, whose research focuses on the underlying mechanics (fracture, fatigue, and soft elasticity) of LCEs to develop actuators with enhanced mechanical properties through advanced fabrication methods. The search then radiated outward through reference lists of these papers to identify additional relevant studies, complemented by searches of Web of Science, Google Scholar, and Scopus. Unlike existing literature reviews written for expert audiences, this review is written from a student perspective, prioritizing clarity and logical progression over technical density. It explains complex concepts in plain language and is anchored in a mechanics-driven framework that reflects the author's research interest, helping student readers understand how the fundamental materials science behind LCE connects to robotic function. By analyzing recent progress and remaining challenges, this paper aims to clarify the current state of the field and identify directions for future research in adaptive and multifunctional soft robotic systems.

## **FUNDAMENTALS OF LIQUID CRYSTAL ELASTOMERS**

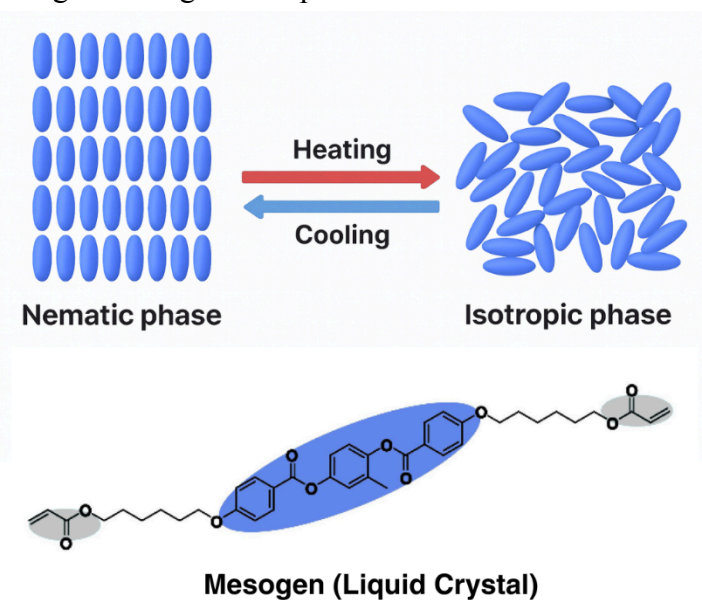
Liquid crystal elastomers (LCEs) are lightly cross-linked polymer networks that incorporate mesogenic units, molecules capable of forming liquid crystalline phases into their molecular structure. What makes LCEs unique is the coupling between molecular alignment and macroscopic elasticity. In other words, changes that occur at the molecular level directly translate into visible, large-scale shape changes in the material.

In the nematic phase, the mesogenic units align along a common direction known as the director. This alignment stretches and organizes the surrounding polymer chains, creating anisotropy, meaning the material behaves differently depending on direction. When the material is heated above its nematic-isotropic transition temperature ( $T_{NI}$ ), this ordered alignment breaks down. The mesogens become randomly oriented, and the polymer chains return to a more entropically favorable, coiled

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configuration. As a result, the material contracts along the original director axis (Warner & Terentjev, 2007). This phase transition is reversible. When the material cools below  $T_{NI}$ , the mesogens realign, restoring the original elongated shape.



**Figure 1.** Fundamental actuation mechanism of LCEs. Adapted from Warner & Terentjev (2007).

The ability of LCEs to directly convert thermal or optical energy into mechanical work distinguishes them from conventional mechanical actuators. Instead of relying on gears, pistons, or motors, LCEs operate through internal molecular rearrangement. The direction and magnitude of actuation are determined during fabrication, when the molecular director field is programmed through controlled alignment and crosslinking. As a result, a single monolithic LCE component can be designed to bend, twist, contract, or curl depending on how the mesogens are oriented.

Several parameters are used to evaluate the performance of LCE actuators. Maximum strain describes the relative change in length during actuation and determines the achievable range of motion. Generated stress refers to the force produced per unit cross-sectional area, while work density measures the mechanical work output per unit volume. Together, these metrics describe the actuator's strength and energy output. Response time is another critical factor and represents how quickly the material deforms after stimulation. Cycle life refers to how many actuation cycles the material can undergo before performance degradation occurs. Finally, energy efficiency measures the ratio of useful mechanical work to total energy input, which is especially important for portable or battery-powered systems. Understanding these fundamental mechanisms and performance parameters is essential for evaluating how fabrication strategies and actuation modes influence overall system behavior.

## **PERFORMANCE COMPARISON WITH OTHER SOFT ACTUATORS**

Designing an effective soft robotic actuator requires balancing multiple performance factors, including strain, force output, response speed, durability, and system complexity. No single material excels in every category. Instead, each technology presents trade-offs. Liquid crystal elastomers occupy a distinctive position among soft actuators because they combine relatively large strain with moderate force output and wireless activation capability.

A central trade-off in actuator design is between force output and achievable strain. Shape memory alloys generate extremely high work densities, often exceeding 1000 kJ per cubic meter. This makes them suitable for applications that require substantial force. However, they typically achieve only 3% to 8% strain and remain mechanically rigid due to their metallic structure. In contrast, LCEs produce lower stress but can undergo much larger deformations, with reported strains reaching up to 400%. This high strain capacity allows for more life-like bending, curling, and contraction behaviors that resemble biological muscle.

Response speed represents another important consideration. Dielectric elastomers can operate at millisecond time scales, making them attractive for high-frequency tasks. However, they require high voltages in the kilovolt range, which introduces safety concerns and increases system complexity. LCEs generally respond more slowly when thermally activated, with response times ranging from fractions of a second to several seconds depending on thickness and heating conditions. Despite this limitation, LCEs can be triggered using moderate heat or light without the need for high-voltage electronics, simplifying integration in portable systems.

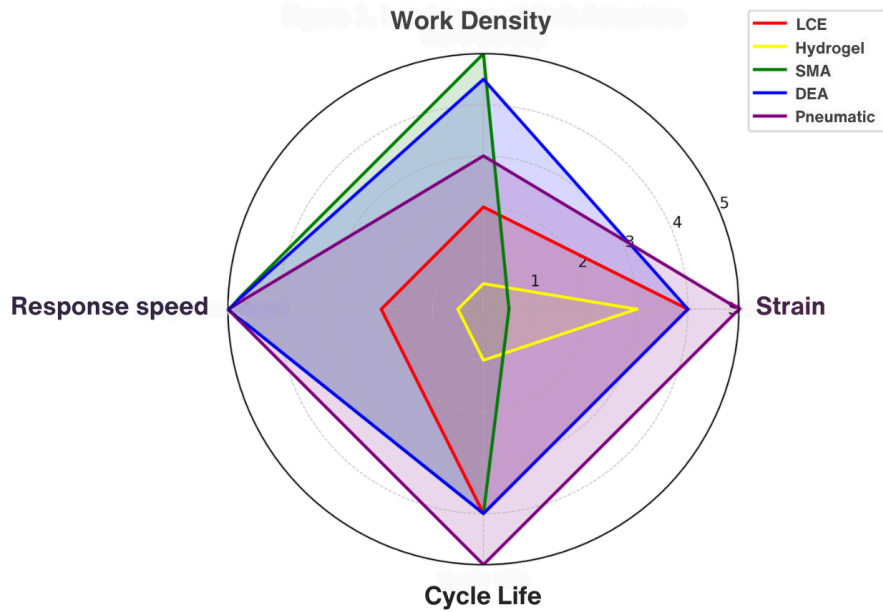
System integration is also a key factor. Pneumatic actuators are widely used because of their reliability and high force output. They can operate for millions of cycles with consistent performance. However, they depend on external air pumps, tubing, and control hardware. This additional infrastructure increases system size and reduces portability. LCEs offer a more integrated solution because the actuation mechanism is embedded directly within the material. Movement is encoded in molecular alignment, allowing the actuator to function without external compressors or tethered systems.

Durability and environmental stability further distinguish these materials. Hydrogels can stretch beyond 1000% strain and are often biocompatible. However, they are sensitive to dehydration and typically exhibit limited cycle life, often fewer than one thousand cycles. LCEs are more robust under repeated actuation and can maintain performance across tens of thousands of cycles, although thermal hysteresis and gradual material fatigue remain challenges.

When evaluated across these dimensions, LCEs do not necessarily outperform every alternative in a single metric. Instead, their strength lies in offering a balanced combination of large strain, moderate force, wireless activation, and material integration. This intermediate performance profile makes them particularly attractive for applications that require both flexibility and functional independence.

**Table 1.** Performance and operational constraints comparison of soft actuator technologies.

Materials	Max Strain	Work Density	Response Time	Cycle Life	Major Limitations
LCE	Up to 400%	10 – 200 kJ/m <sup>3</sup>	100 ms – 10 s	10 <sup>3</sup> – 10 <sup>5</sup> cycles	Thermal hysteresis and slow cooling cycles
Hydrogel	Up to 1000%	< 10 kJ/m <sup>3</sup>	Seconds to Minutes	< 10 <sup>3</sup> cycles	Low force output and risk of dehydration
DEA	10% - 300%	10 – 150 kJ/m <sup>3</sup>	< 10 ms	> 10 <sup>6</sup> cycles	High operating voltages (kV range)
SMA	3% - 8%	> 1000 kJ/m <sup>3</sup>	100 ms – 1 s	10 <sup>3</sup> – 10 <sup>4</sup> cycles	Rigidity and limited range of motion
Pneumatics	> 500%	50 – 500 kJ/m <sup>3</sup>	10 ms – 100 ms	> 10 <sup>6</sup> cycles	Requires bulky external pumps and tethers



**Figure 2.** Multi-axis performance comparison of major soft actuation technologies. Metrics are normalized on a qualitative scale (1–5) based on current literature benchmarks.

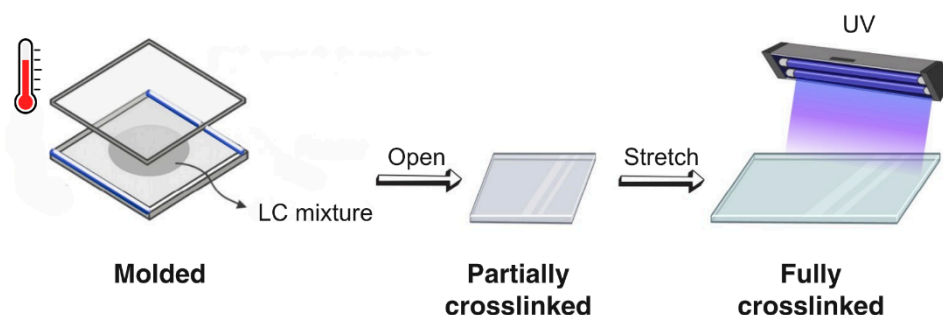
## FABRICATION AND ALIGNMENT STRATEGIES

The actuation behavior of liquid crystal elastomers depends strongly on how the mesogenic units are aligned during fabrication. Because deformation occurs preferentially along the molecular director, precise control over alignment is essential for predictable and programmable motion in soft robotic systems (Zhu et al., 2024). As a result, fabrication strategies focus not only on shaping the material but

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also on prescribing spatially defined molecular orientation. A central challenge across all methods is the trade-off between alignment precision and manufacturing scalability. Techniques that achieve high-resolution director control typically require laboratory conditions and produce small-area samples, while scalable methods often sacrifice local alignment accuracy.

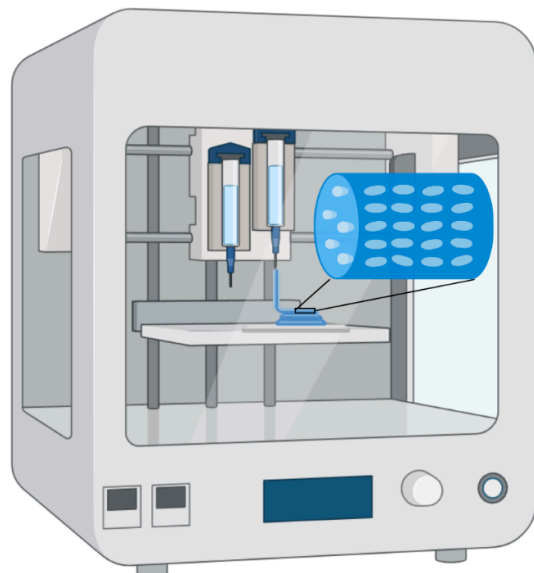
The traditional method for fabricating aligned LCEs relies on a two-step crosslinking process that separates molecular alignment from final network stabilization. In the first stage, a precursor mixture undergoes partial crosslinking to form a soft, polydomain elastomer. This intermediate material retains sufficient molecular mobility to allow reorientation of mesogens. Mechanical stretching is then applied to align the molecular domains along a defined axis. In the final stage, additional curing, often through ultraviolet irradiation, permanently locks the network into a monodomain state with uniform anisotropy. Although this approach is robust and widely used, it primarily produces uniform uniaxial alignment and therefore limits actuation to simple contraction or extension along a single direction.



**Figure 3.** LCE fabrication using two-step crosslinking with mechanical stretching. Adapted from Jiang et al. (2024)

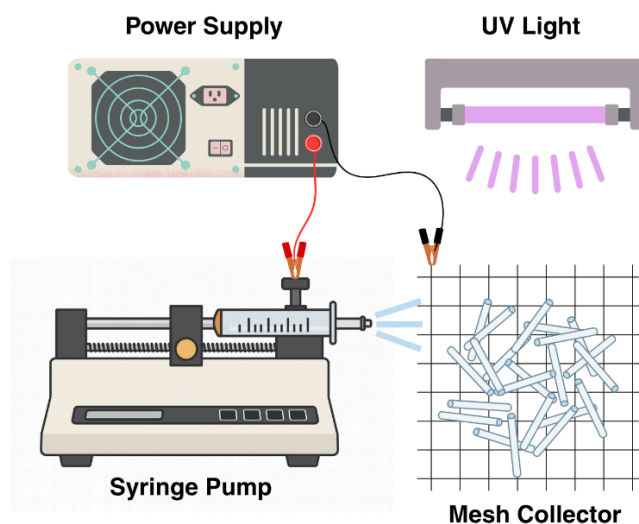
To enable more complex deformations, researchers have developed techniques that create spatial variations in director orientation. By locally controlling alignment, different regions of a single LCE component can respond differently to the same stimulus. This spatial heterogeneity allows for bending, twisting, and other multi-axis deformations that more closely resemble biological motion.

3D printing and direct ink writing (DIW) have significantly expanded design flexibility. In this approach, shear forces generated during extrusion align mesogens along the print path. Subsequent curing preserves this orientation. By varying the printing direction layer by layer, it is possible to program complex director fields within three-dimensional geometries. This method enables the fabrication of actuators with tailored deformation patterns and integrated structures (Song et al., 2022; Wang et al., 2020). However, printing speed and ink formulation constraints currently limit large-scale manufacturing. Furthermore, the resolution of alignment is inherently tied to nozzle diameter and print path, meaning that higher precision comes at the cost of longer fabrication times, a trade-off that remains unresolved for high-throughput production.



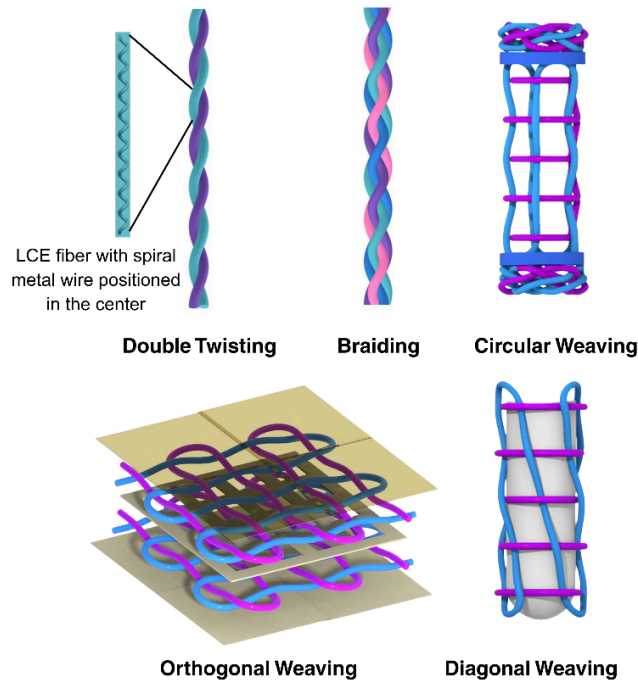
**Figure 4.** LCE fabrication using 3D printing.

Electrospinning offers an alternative route for producing highly aligned LCE microfibers. During this process, a high voltage electric field draws a polymer solution into fine fibers that elongate as solvent evaporates. The elongational flow naturally aligns mesogens along the fiber axis. After curing, the resulting fibers exhibit strong anisotropy and rapid thermal response due to their small diameter. He et al. (2021) demonstrated electrospun LCE fibers capable of fast and reversible actuation with good durability. While electrospinning is effective for producing aligned fibers, assembling these fibers into large and structurally complex actuators remains challenging.



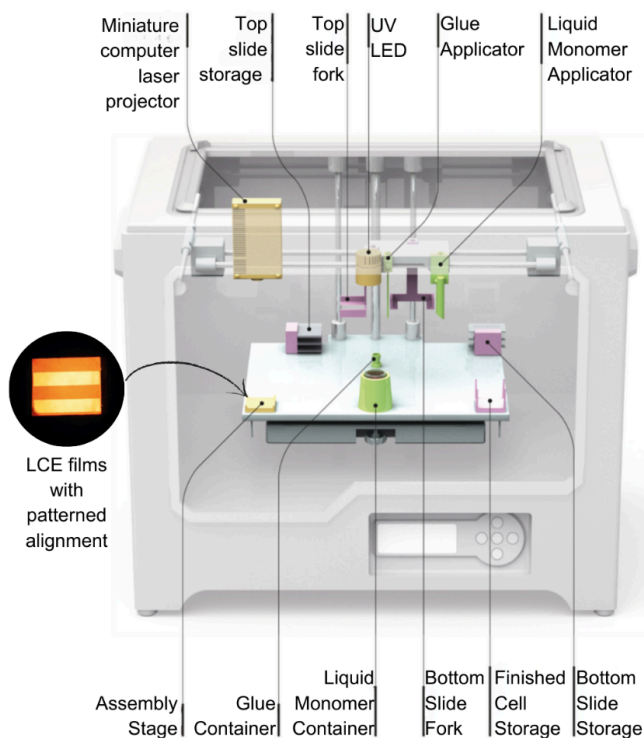
**Figure 5.** LCE fabrication using electrospinning. Adapted from He et al. (2021)

Fiber weaving represents a scalable strategy for integrating LCE fibers into textile architectures. Extruded and cured fibers can be interlaced using controlled weaving patterns to create macroscale assemblies. By adjusting fiber orientation and weave geometry, researchers can tune stiffness, force output, and actuation direction. These woven structures enable coordinated motion such as bending or crawling across large areas. Although weaving supports scalability and mechanical robustness, precise local control of director orientation is more limited than in printing or electrospinning approach.



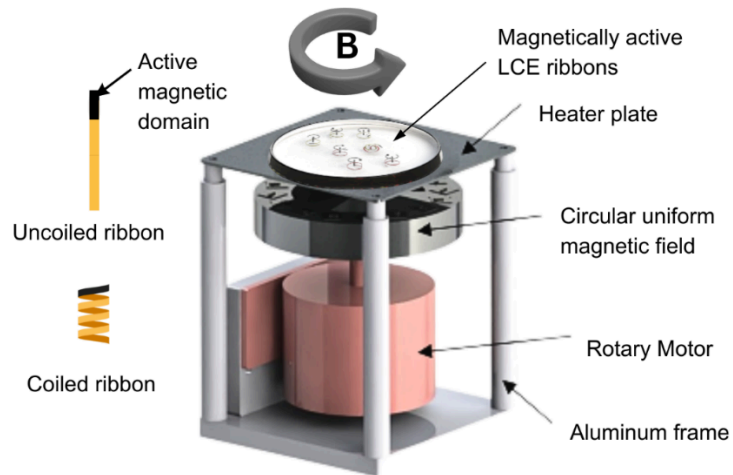
**Figure 6.** LCE fabrication using fiber weaving. Adapted from Yang et al (2025)

Photopatterning provides high-resolution spatial control of mesogen alignment in thin films. In this technique, a photosensitive alignment layer is exposed to linearly polarized ultraviolet light, which orients surface molecules. The LCE precursor deposited on top adopts this orientation, and subsequent polymerization locks the programmed director pattern in place. Sequential exposures can generate complex, nonuniform alignment fields within a single film (Grabowski et al., 2022). ~~This method enables accurate and repeatable fabrication of shape-morphing films, although it requires careful optical control and may be less practical for thick or large area structures.~~ Photopatterning achieves the highest spatial resolution of any alignment technique, capable of producing micrometer-scale director variations. The trade-off is equally extreme: the method is largely limited to thin films, and scaling to thick or large-area structures remains impractical.



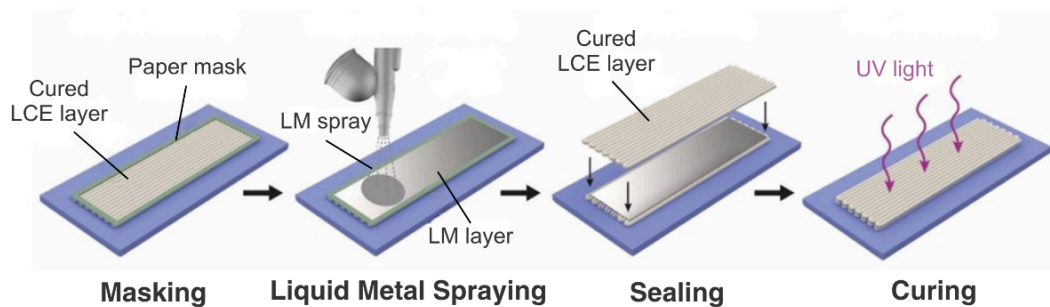
**Figure 7.** Automated photo-aligned LCE film fabrication. Adapted from Grabowski et al. (2022)

Magnetic field-assisted alignment has recently emerged as another strategy for programming orientation. In this approach, magnetic nanoparticles are dispersed within the precursor mixture. Application of external magnetic fields during printing or curing aligns the mesogens along controlled directions. Wang et al. (2024) demonstrated a voxel-based magnetic programming technique that produced spatially varied director fields within a single structure. This approach enables reversible shape transformations and magnetic responsiveness within the same material. ~~However, uniform nanoparticle dispersion and precise field calibration remain technical challenges.~~ However, two significant challenges persist. First, achieving uniform nanoparticle dispersion without agglomeration is nontrivial. Second, calibration of magnetic fields for complex director patterns requires sophisticated equipment and computational modeling. These barriers currently restrict magnetic alignment to laboratory settings.



**Figure 8.** Schematic illustrating the mechanism that drives shape change and entanglement in magnetically active LCE ribbons. Adapted from Wang et al. (2024)

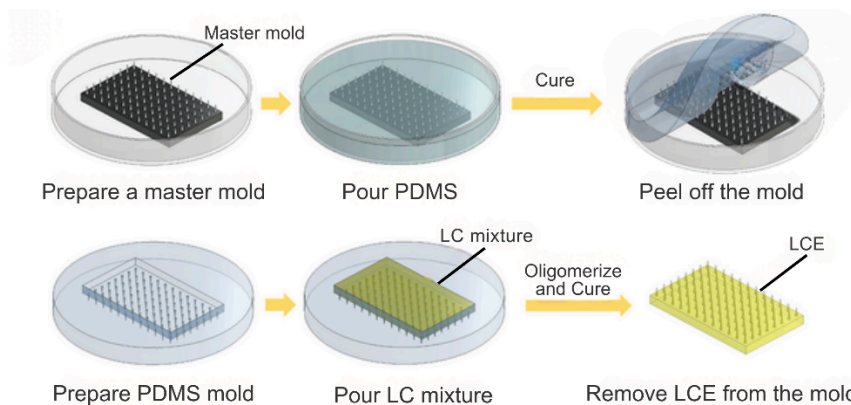
Recent work has also explored multifunctional composite systems. For example, liquid metal particles can be incorporated into LCE matrices to improve thermal and electrical conductivity. These composites enable electrothermal activation via Joule heating and can achieve faster response times than purely thermally driven systems (Maurin et al., 2024). While promising, the addition of fillers can alter the mechanical properties of the LCE network, potentially reducing actuation strain or increasing hysteresis. The field has not yet established general design rules for balancing multifunctionality against actuation performance, representing an open area for future investigation.



**Figure 9.** Fabrication steps of LCE-LM composite. The multi-step process involves masking a cured LCE layer, followed by liquid metal spraying to create conductive pathways. The system is then sealed with a top LCE layer and cured under UV light to form an integrated, multifunctional actuator capable of rapid electrothermal response. Adapted from Maurin et al. (2024).

Microfabrication and lithography-based methods have been applied to LCEs to achieve miniaturized actuators. Techniques such as soft lithography and projection lithography can produce micropatterned LCE films with tailored director fields, enabling highly localized actuation at small scales. These methods

are especially promising for biomedical devices and microrobotics where precision and biocompatibility are critical (Ince et al., 2024; Wiersma and Zeng, 2021).



**Figure 10.** Microfabrication of LCEs via soft lithography. The process involves casting a PDMS mold from a master template, infiltrating the microstructures with an LC precursor, and subsequently curing to produce high-resolution, miniaturized LCE actuators. Adapted from Ince et al. (2024).

Together, these fabrication strategies demonstrate that alignment control is the central determinant of LCE functionality. By tailoring director orientation across multiple length scales, researchers can program complex and application-specific motion into a single continuous material. ~~Continued improvements in scalability, reproducibility, and integration will be essential for translating these laboratory methods into industrial manufacturing processes.~~ Across all fabrication methods, a persistent gap remains: no single technique simultaneously achieves high alignment resolution, three-dimensional complexity, large-area scalability, and rapid production throughput. Researchers must therefore select methods based on application-specific priorities, with biomedical devices favoring photopatterning and electrospinning while industrial applications lean toward weaving and DIW. This diversity reflects the fact that the field has not yet converged on a dominant fabrication paradigm. Continued improvements in scalability, reproducibility, and integration will be essential for industrial translation. A promising direction is hybrid fabrication, which combines two or more techniques (e.g., printing followed by magnetic alignment or weaving of electrospun fibers) to leverage the strengths of each while mitigating individual limitations.

## ACTUATION MECHANISMS

To function as active components in soft robotic systems, liquid crystal elastomers must be stimulated by external inputs that trigger mechanical deformation. Multiple actuation strategies have been developed to improve response speed, control precision, and energy efficiency. These approaches vary in activation mechanism and practical constraints.

Thermal activation remains the most widely studied and mechanically robust actuation mode for LCEs. Heating the material beyond its transition temperature reduces molecular alignment, leading to macroscopic contraction along the programmed director. Early studies relied on external heating sources,

which limited response speed and spatial control. Subsequent work incorporated conductive fillers to enable internal electrothermal heating, improving uniformity and controllability (Ware et al., 2015). Recent developments have focused on improving thermal efficiency and durability. Agrawal et al. (2025) reported reinforced LCE systems that maintained high strain while enhancing mechanical toughness under repeated cycling. Thermally activated LCEs commonly achieve strains between 40% and 300%, depending on formulation and alignment. However, response frequency remains constrained by heat transfer and cooling rates, particularly in thicker structures.

Optical activation provides a non-contact alternative that enables localized and spatially selective control. Two primary mechanisms are employed. In photoisomerization, embedded molecular switches change conformation upon light exposure, disrupting mesogen alignment. In photothermal systems, light-absorbing dopants convert optical energy into localized heat, indirectly driving the phase transition. This approach allows high spatial resolution and remote operation. ~~De Haan et al. (2014) demonstrated light-driven LCE films capable of wave-like motion.~~ Gelebart et al. (2017) demonstrated light-driven LCE films capable of continuous, directional wave-like motion under constant light illumination. Optical systems typically produce strains ranging from 5% to 100%, depending on material composition and light intensity. Limitations include potential photobleaching of chromophores and restricted penetration depth in thicker or opaque materials.

Magnetic activation enables wireless stimulation through external magnetic fields. In magnetothermal systems, embedded magnetic nanoparticles generate localized heating under alternating magnetic fields, inducing contraction. Alternatively, magnetic torque can directly reorient dipoles within the material, producing rapid deformation. Dana et al. (2024) demonstrated magnetic LCE systems capable of response times below 100 milliseconds with strains approaching 100%. Magnetic actuation is particularly attractive for biomedical applications because magnetic fields can penetrate biological tissue. However, the requirement for specialized external field generators may limit portability in certain applications.

Electrical activation is commonly achieved through Joule heating. Conductive networks embedded within the LCE matrix convert applied voltage into thermal energy, which then drives actuation. This strategy facilitates integration with portable power sources and digital control systems. Wang et al. (2023) reported electrothermally driven LCE actuators with sub-second response times and strains ranging from 10% to 200%. While electrical activation improves controllability, repeated high-frequency cycling requires effective thermal management to prevent overheating and long-term degradation.

Solvent-based activation relies on the absorption of chemical vapors or liquids. Absorbed molecules act as plasticizers, modifying the effective transition temperature and enabling deformation at ambient conditions. Arachchige et al. (2025) demonstrated environmentally responsive LCE grippers that operate without continuous power input.

Recent research has explored hybrid approaches that combine multiple activation strategies to overcome the limitations of individual strategies. For example, liquid metal inclusions increase thermal conductivity and enable rapid electrothermal actuation. Maurin et al. (2024) reported composite systems achieving

response times below 50 milliseconds by improving internal heat transfer efficiency. Some hybrid architectures also incorporate closed-loop feedback systems, allowing deformation to be monitored and adjusted in real time. While these multifunctional systems enhance responsiveness and control, they require precise fabrication to maintain material stability and consistent phase behavior.

No single actuation method satisfies all performance criteria. The choice of stimulus therefore depends on application-specific priorities. Thermal actuation remains the best choice for applications requiring high strain and mechanical robustness where response speed is secondary (e.g., assistive devices, prosthetics). Optical actuation excels in thin-film, high-resolution applications such as microgrippers and surface morphing. Magnetic actuation is uniquely suited for biomedical implants where wireless operation and tissue penetration are essential. Electrical actuation offers the most straightforward integration with digital control systems, making it attractive for untethered soft robots. Solvent-based actuation occupies a niche for passive, low-speed, power-free operation. Hybrid approaches, while still maturing, offer the most direct pathway toward overcoming the fundamental trade-offs that limit single-mode actuators. The field lacks standardized performance benchmarks (e.g., response time measured under identical conditions, cycle life at defined strain amplitudes), making direct comparisons between actuation modes difficult. Establishing such benchmarks would significantly accelerate method selection and device design.

## **APPLICATIONS FOR SOFT ROBOTICS**

The ability of liquid crystal elastomers to undergo large, reversible, and programmable shape changes has enabled a wide range of soft robotic applications. Because deformation is encoded at the molecular level during fabrication, LCE actuators can produce complex motion without rigid mechanical components. Over the past decade, research has demonstrated their use across multiple length scales, from microscale biomedical devices to macroscale locomotion systems.

### **Artificial Muscles and Motor Units**

One of the primary motivations for LCE research is the development of artificial muscles capable of generating large strain while remaining lightweight and compliant. Wang et al. (2023) reported an electrothermally driven motor unit composed of bundled LCE strips designed to mimic skeletal muscles. The system achieved strains of approximately 200% with response times near one second and maintained performance over more than 1000 cycles. By structuring the actuator into aligned bundles, the design improved heat distribution and mechanical output. These results suggest that LCE-based muscle analogues may be suitable for assistive devices, prosthetics, and compact robotic systems.

### **Biomimetic Locomotion**

Programmable alignment has enabled LCE actuators to replicate biological modes of locomotion. Song et al. (2022) used direct ink writing to fabricate segmented actuators with spatially defined director orientations. When activated sequentially, the structure produced an inchworm-like crawling motion. This

work demonstrated how alignment patterning can translate simple contraction into coordinated, directional movement.

At larger scales, textile-inspired architectures have been explored to improve mechanical robustness and scalability. Yang et al. (2025) developed woven fiber assemblies in which microscale LCE fibers were interlaced to form macroscale actuators. These systems achieved multi-degree of freedom motion and substantial load-bearing capacity while maintaining flexibility. The weaving approach illustrates how microscale actuation can be amplified into larger mechanical systems.

### **Adaptive Grippers and Interfacial Adhesion**

Soft robotic manipulation requires actuators that can conform to irregular surfaces without damaging delicate objects. LCEs are well-suited for this purpose due to their low elastic modulus and programmable curvature. Annapooranan et al. (2024) investigated LCE-based grippers that combine elasticity with tunable adhesive interfaces. The material's compliance allows it to conform to microscopic surface features, increasing effective contact area and grip strength. These systems demonstrated reliable grasping under significant deformation, suggesting potential use in biomedical handling and precision manufacturing.

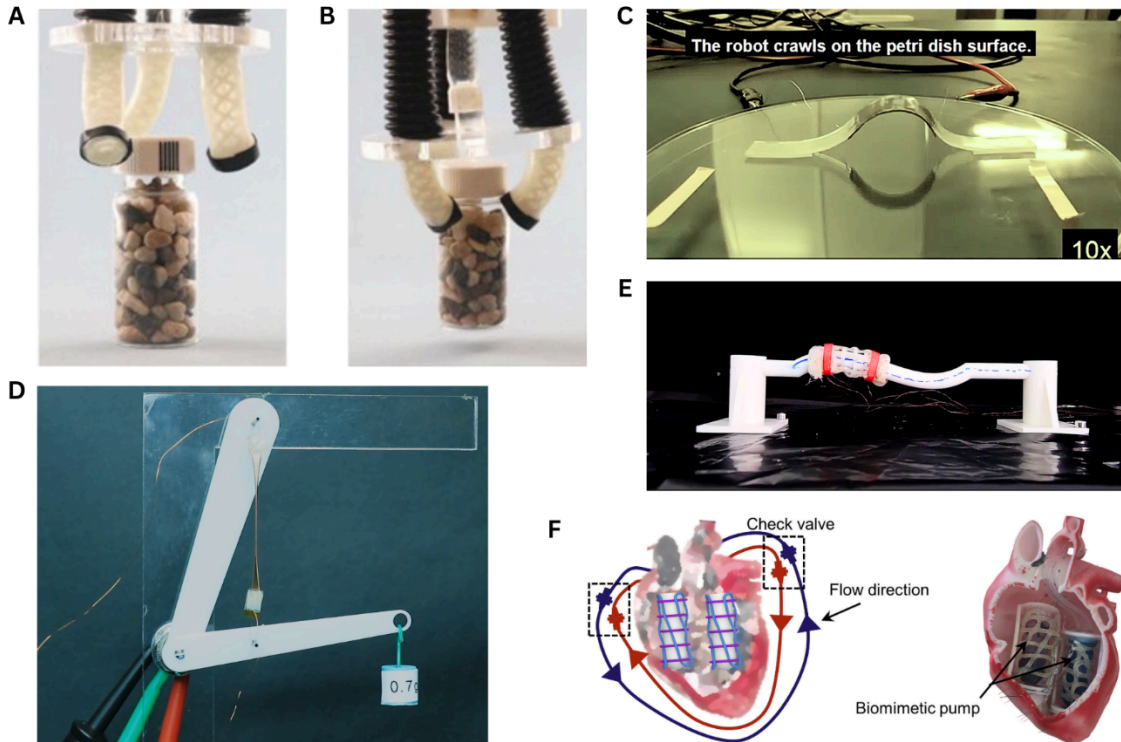
### **Self-Sensing and Biomedical Integration**

Recent research has focused on integrating sensing capabilities directly into LCE actuators. El Helou et al. (2024) developed miniaturized devices with embedded conductive pathways that enable real-time monitoring of resistance or capacitance during deformation. This self-sensing functionality allows the actuator to detect its own deformation without external sensors. Such closed-loop capability is particularly relevant for wearable robotics and implantable biomedical devices, where compactness and functional integration are essential.

Due to their mechanical compliance, LCEs are also being investigated for biomedical applications that require compatibility with soft tissue. Examples include cardiac assist devices, artificial sphincters, and responsive therapeutic implants. Matching the mechanical impedance of biological tissue reduces the risk of damage and improves long-term performance.

### **Environmentally Responsive Systems**

LCEs have also been explored for environmentally adaptive systems. Sepehri et al. (2025) demonstrated a multi-responsive material that combines light sensitivity with thermochromic behavior. By embedding functional pigments within the elastomer matrix, the system could alter both surface texture and optical appearance in response to environmental conditions. While initially investigated for adaptive camouflage, similar principles may be applied to smart surfaces and energy management systems.



**Figure 11.** Representative applications of LCE actuators in soft robotics. (A) Soft gripper twisting the cap of a vial (He et al., 2019). (B) Soft gripper grasping and lifting the vial (50 g) (He et al., 2019). (C) Inchworm-inspired crawling robot (Song et al., 2022). (D) Artificial motor unit lifting weight (Wang et al., 2023). (E) Multifunctional crawling robot (Yang et al., 2025). (F) Cardiac muscle-inspired biomimetic pump (Yang et al., 2025). A supplementary downloadable video is available upon request.

## CHALLENGES AND FUTURE DIRECTIONS

Despite significant progress over the past decade, several technical and practical challenges continue to limit the widespread deployment of liquid crystal elastomers in soft robotic systems. Addressing these constraints is essential for transitioning LCEs from laboratory prototypes to reliable, large-scale technologies.

### Thermal Response Limitations

The most persistent limitation in LCE systems remains response speed under thermal activation. Because many LCE actuators rely on heating and cooling across a phase transition, actuation frequency is constrained by heat transfer rates. Thick or bulk geometries experience slower thermal diffusion, which reduces responsiveness in dynamic applications.

Recent approaches have sought to improve heat dissipation through bundled fiber architectures and integrated cooling systems (Sepehri et al., 2025). Induction-heated and liquid metal composite systems have also demonstrated reduced response times by improving internal thermal conductivity (Maurin et al., 2024). While these strategies have narrowed the performance gap relative to faster electroactive materials, thermal management remains a central engineering challenge.

### **Mechanical Fatigue and Long-Term Durability**

Repeated actuation subjects LCE networks to cyclic mechanical and thermal stresses. Over time, this can lead to gradual mesogen misalignment, microcrack formation at crosslinking sites, or changes in transition temperature. Although many systems maintain performance over tens of thousands of cycles, further improvement is required for industrial and biomedical deployment.

Chemical reinforcement strategies have shown promise in improving durability. Chain entanglement reinforcement enhances mechanical toughness without substantially reducing strain capacity (Agrawal et al., 2025). Double network architectures and optimized crosslink densities have also been investigated to reduce fatigue accumulation (Lin et al., 2022). Continued material design efforts will be necessary to balance flexibility with long-term structural stability.

### **Fabrication Scalability**

While precise director programming has been demonstrated through photopatterning, direct ink writing, and magnetic alignment, maintaining uniform orientation across large areas remains technically demanding. Many advanced alignment techniques require controlled laboratory environments and careful calibration. Scaling these processes to industrial manufacturing levels introduces challenges related to reproducibility, throughput, and cost.

Emerging high-throughput approaches, including automated textile weaving and roll-to-roll processing of aligned films, may provide viable pathways toward scalable production. However, further optimization is required to preserve alignment fidelity during large-scale fabrication.

### **Integration of Sensing and Control**

In their simplest form, LCEs function as open-loop actuators. Without integrated sensing, external feedback systems are required to monitor strain and regulate performance. Embedding conductive pathways, liquid metal networks, or carbon-based fillers enables self-sensing capabilities by correlating electrical changes with deformation (El Helou et al., 2024).

Although these multifunctional systems enhance autonomy, they introduce additional fabrication complexity and potential trade-offs between mechanical softness and electrical performance. Achieving reliable closed-loop control within a fully compliant architecture remains an active area of research.

## CONCLUSION

LCEs represent a distinctive class of responsive polymers that translate molecular alignment into macroscopic deformation. Over the past decade, advances in fabrication ranging from 3D printing and fiber weaving to bundled actuators with integrated cooling have significantly expanded the design space. Likewise, novel actuation modes, including hybrid systems with liquid metals and photoresponsive composites, have accelerated progress toward practical applications. As we move toward 2030, research trends point toward multifunctional composites, scalable fabrication methods, self-sensing integration, and biomedical applications. With continued innovation in alignment, reinforcement, and multimodal actuation, LCEs are poised to play a central role in the next generation of adaptive, programmable, and biocompatible soft robots.

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