A Review on Soft Planar Mechanisms: Modeling and Actuation for Robotic Applications

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ABSTRACT

Soft planar mechanisms combine compliant materials, bio-inspired designs, and hybrid actuation strategies to extend classical planar kinematics into adaptive robotic systems. This review is based on studies that were published between 2020 and 2025, and sourced from Scopus, Web of Science, and Google Scholar databases. It is a synthesis of recent advances in actuation technologies, such as pneudraulic actuators, Organic Photovoltaic–Dielectric Elastomer Actuators (OPV-DEAs), and McKibben textile muscles, and biologically inspired structures, such as avian claws and origami-based exoskeletons. It further discusses the development of intelligent modeling and control, such as Koopman-based Model Predictive Control (MPC) and biLSTM neural networks that can be used to increase real-time flexibility and accuracy. Important constraints associated with reproducibility, fatigue performance, and variability of fabrication are taken care of by benchmarking activity and new standardization. The review concludes with a roadmap focusing on embedded sensing, sustainable materials, and scalable deployment for rehabilitation, wearable robotics, and adaptive soft systems.

Keywords-soft planar mechanisms; compliant actuation; bio-inspired robotics; hybrid modeling; soft robotic materials

I. INTRODUCTION

Soft planar mechanisms constitute a new class of robotic systems combining the compliance of soft materials and the predictable geometry of planar kinematics. These systems operate in two-dimensional workspaces, and their structures and actuators are made flexible but controllable [1-3]. By integrating actuation into soft materials, soft planar mechanisms enable smooth adaptive motions that are non-existent in hard-bodied mechanisms. This ability enables them to interact with humans safely and be able to adapt to dynamic environments [4-6].

Traditional planar mechanisms, such as slider-crank linkages, parallel manipulators, and four-bar systems, are popular due to their easy and robust analysis and their stable and easy-to-understand analytical models. In contrast, soft planar mechanisms have compliance distributed across their body, and they deform continuously [2, 3]. Moving from discrete joints to material-based morphing allows these robots to shape reconfiguration, contact adaptation, and local compliance. Consequently, they ensure geometric controllability while also obtaining the adaptability, safety, and versatility that characterize modern soft robotics [7-9].

Unlike soft continuum robots that employ three-dimensional flexibility as an exploration mechanism, soft planar mechanisms deliberately limit actuation to a flat, 2D exploration mechanism. This simplification compromises spatial versatility for better geometric control, easier fabrication, and better precision in compact, repeatable planar tasks [10]. While continuum robots are excellent for applications, such as endoscopy and exploration, where complex 3D dexterity is required, planar soft actuators are more suitable for assistive devices, wearables, and surgical tools where safety, compactness, and repeatability are the key requirements [11, 12].

This review highlights the latest developments in soft planar mechanisms in terms of actuation methods, bio-inspired mechanisms, and intelligent modeling. It also addresses continuous challenges, such as benchmarking, reproducibility, and scalability issues, and proposes a road map for the development of sustainable, sensor-integrated, and human-centered soft planar system development.

II. ACTUATION METHODS AND MATERIALS

The soft planar mechanisms have also evolved in actuation strategies to be able to achieve higher speed, greater autonomy, and tunable stiffness while retaining compliance. Table I presents the comparison of actuation methods.

Scalability remains a major challenge throughout these actuation strategies. In miniaturized soft actuators, performance losses can arise from reduced force output, slower response, and limited thermal dissipation [13]. Dielectric Elastomer

Actuators (DEAs) tend to be less strained and more fragile at microscales. In contrast, expansion to large systems may bring about pressure control problems, structural support, and energy efficiency problems [14]. Future work should focus on material architectures and actuator morphologies that maintain functionality across size scales and support consistent performance under both miniaturized and large format configurations.

TABLE I. COMPARISON OF ACTUATION METHODS

Actuator type	Max. strain (%)	Bandwidth (Hz)	Force output	Efficiency (%)	Durability (cycles)	Typical applications	Reference
Pneumatic	100–300	<10	5–50 kPa	10–30	10^3–10^4	Adaptive surfaces, planar grasping	[15]
Organic Photovoltaic (OPV)-DEA composite	20–150	10–500	10–100 kPa	40–70	$\geq 10^3$	Energy-autonomous soft swimmers	[16]
Woven McKibben textiles	>200	<5	>14 kg lifting	20–40	$\geq 10^4$	Soft grippers, continuum actuators	[17]
Shape Memory Alloys (SMA) /Magnetic	4–50	1–50	50–200 MPa	10–20	$\geq 10^3$	Bistable, remote-control systems	[18]
Hybrid soft–rigid	Variable	Variable	Variable	Variable	–	Precision + compliance	[19]

A. *Pneudraulic Actuation*

Pneudraulic actuation uses a combination of pneumatic and hydraulic systems as a serial system combining the high compliance of a pneumatic inflation system with the force amplification of a hydraulic system. The hybrid mechanism shown in Figure 1, maximizes the fluid-structure interaction and increases system responsiveness, offering the best solution [18]. Authors in [15] noted that the pneudraulic actuators have a 52.6% rate of increase in the actuation speed and a 17.2% cut in operational noise during PID control, in contrast to traditional pneumatic-only systems. The advancements make pneudraulics an attractive choice as a soft robotic system that needs dynamic capabilities and environmental silence.

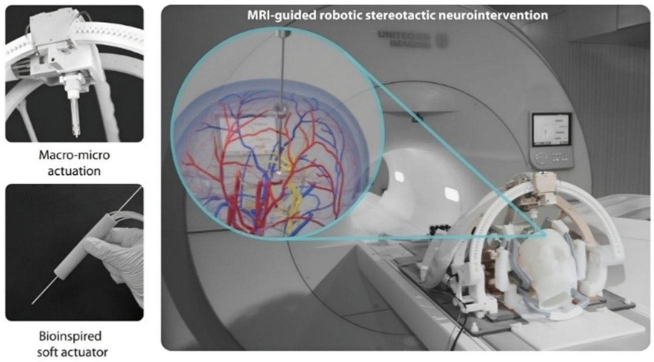

Fig. 1. Hybrid pneudraulic actuation in MRI-guided soft robotics. Reproduced from [18] under CC 4.0 licence [39].

B. *DEAs with Energy Harvesting*

The DEAs are known for their high energy density and fast response. This is made possible by innovations that have offered OPV-DEAs, as depicted in Figure 2, allowing energy harvesting and actuation at the same time [16]. Authors in [16] suggested that such systems have a maximum bending degree of 15.6° with stable performance of over 1,000 cycles. Moreover, the integrated photovoltaic layer produced 1.35 mW of electrical power at ambient light, which has high potential for self-powered soft robotic applications.

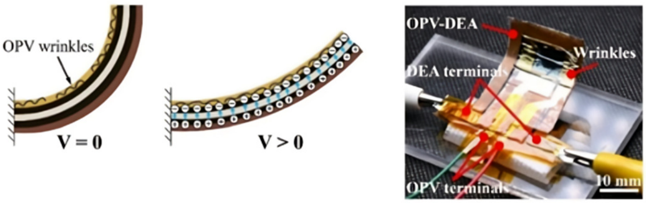

Fig. 2. OPV-DEA system enabling self-powered bending actuation. Reproduced from [16] under CC 4.0 licence [39].

C. *Woven McKibben Textiles for Variable Stiffness*

Previously operated in the context of their contractile properties, McKibben actuators have been developed to be integrated into woven textile designs. This design is a pneumatic actuated-muscle combined with the flexibility of the fabrics, thus producing systems that are both comfortable and highly mechanized. The findings in [17] indicated that these woven structures had more than five times greater tunability in stiffness and that they could be used to carry up to 14.7 kg, hence they can be applied in wearable robotics and load-adaptive structures.

D. *Hybrid Material Systems with Magnetic and SMA Components*

Hybrid soft actuators using magnetic particles or SMAs enable further action and responsiveness to be controlled. Such materials provide other actuation modes, such as remote magnetic manipulation and thermally driven transformations. According to [20], hybrid structures optimize the accuracy as well as the flexibility of soft planar frameworks, and they can be used in applications that demand the utilization of multiple axes of movement and fine control.

III. BENCHMARKING FRAMEWORK AND METRICS

Soft planar mechanisms exhibit wide diversity in materials, actuation modes, and testing methods. To enable meaningful comparison, five quantitative metrics were selected based on their frequent use in high-impact empirical studies and relevance to actuator performance: maximum strain, force density, response time, durability, and energy efficiency [21]. These measures are derived from peer-reviewed studies on state-of-the-art soft planar actuators. The values provided in Table II denote representative performance ranges reported in experimental literature rather than formally standardized testing conditions [14]. Providing a visual, side-by-side comparison, as in Table I, helps clarify performance trade-offs across actuation technologies.

TABLE II. BENCHMARKING METRICS AND TYPICAL RANGES

Metric	Definition/relevance	Typical range	Common challenges
Maximum strain or deflection	Deformation capability under actuation	10–300% (DEA), 10–50° (pneumatic)	Inconsistent definitions and neglect of parasitic stiffness [14]
Force density/torque per volume	Output normalized to actuator size	5–200 kPa	Non-uniform stress distribution [21]
Response time/bandwidth	Dynamic capability	<10 Hz (pneumatic), up to 500 Hz (DEA)	Step-response only; neglect of load effects [21]
Durability/cycle life	Resistance to fatigue	10^3–10^5 cycles	Lack of standardized testing [14]
Energy efficiency/work density	Energy conversion performance	>50% or >10 J/kg desirable	Hysteresis, leakage, and nonlinear losses [22]

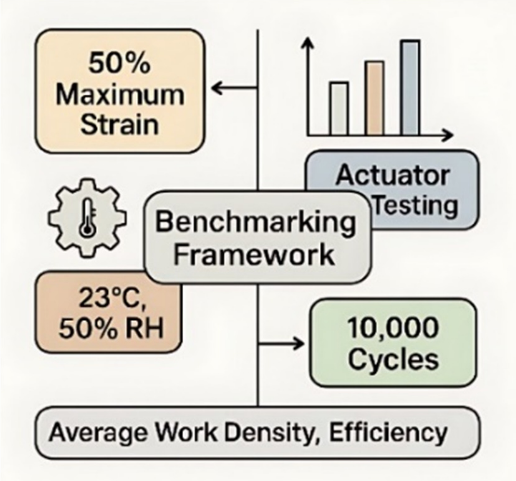

Fig. 3. Visual benchmarking framework for soft planar actuator testing.

To standardize reporting, actuators should be tested at 50% of their maximum strain for 10,000 cycles at 23 ± 2 °C and 50 ± 5% relative humidity, as illustrated in Figure 3. Average work density and efficiency should be calculated from at least three independent trials

IV. BIO-INSPIRED STRUCTURAL DESIGNS

Biological nature offers numerous strategies for motion, which, adaptively, combine compliance, adaptability, and energy efficiency. These principles are more and more abstracted into the design of engineered architectures for soft planar actuation, which allow for systems that can dynamically deform, self-reconfigure, and possibly experience repeated cyclic loading. Through the abstraction of the biomechanical processes present in animals and plants, researchers have manufactured soft structures with greater adaptability and morphological intelligence.

An example is the avian-inspired continuum claw, as shown in Figure 4, developed in [23], which mimics the grasping mechanics of birds with compliant segmented digits. It is capable of grasping objects with different shapes and orientations with high accuracy and versatility. The mechanical form of the device can be especially adapted to the teleoperated operation or prosthetic manipulation, providing the power grasping and passive adaptability at the same time, without the heavy sensing complex form requirements.

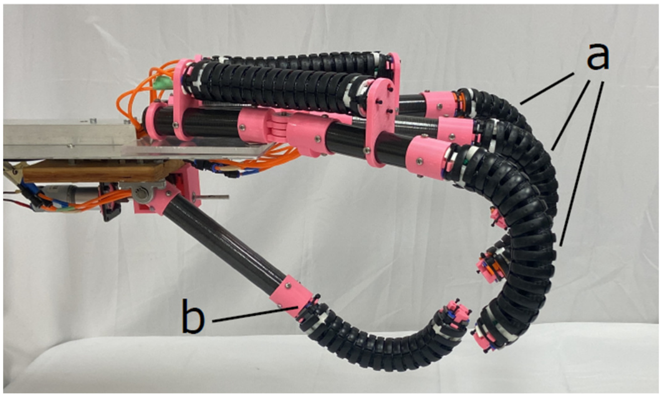

Fig. 4. The Claw, a hybrid rigid-continuum gripper, features: (a) three forward-facing digits and (b) one backward-facing digit. Reproduced from [23] under CC 4.0 licence [39].

Soft growing manipulators, inspired by the tip-growing strategies of vines and roots, achieve elongation through eversion-based actuation, a process where new material inverts outward from the base. Authors in [24] enhanced this concept using Rank Partitioning evolutionary optimization, which iteratively explores high-performance morphologies and control strategies, significantly accelerating design cycles and reducing experimental dependency.

Origami pneumatic exoskeletons, as displayed in Figure 5, inspired by the rigid-flexible architecture of shrimp shells, leverage stable foldable geometries to enhance stiffness while preserving deformability. Authors in [19] demonstrated that wrapping soft actuators with origami exoskeletons enables noninvasive integration, high extension ratios, and substantial load-bearing capacity through mechanical stability.

Unlike methods requiring continuous actuation, these exoskeletons maintain stable configurations with minimal energy input. Their modular design allows for compact storage, rapid deployment, and multimodal assistance, making them promising for hybrid pneumatic–cable robotic arms requiring variable stiffness and precise motion control.

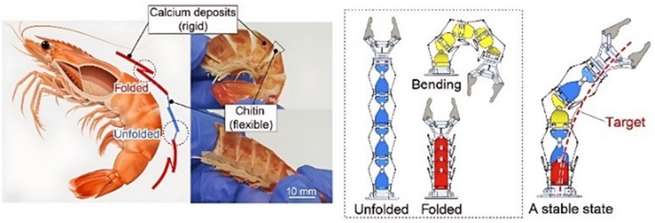

Fig. 5. Shrimp-inspired origami exoskeletons for soft robotic arms. Reproduced from [19] under CC 4.0 licence [39].

To ensure operational longevity and reliability under repeated mechanical cycles, many of these bioinspired architectures incorporate reinforcement strategies such as fabric-embedded elastomers, hybrid joints, or soft–rigid interfaces. These elements reduce the problems associated with fatigue and delamination, particularly in applications where the demands for high cycle life or required load-bearing capacity are high. This type of integration of stiffness-enhancing components not only improves the force output but also facilitates compliant behavior, an important trade-off in soft planar robotics. These designs highlight how mechanical scaffolding and modular configurations can enhance both actuation performance and structural integrity.

In energy harvesting and cyclic motion, self-resetting photothermal actuators have shown great potential. Authors in [20] studied Liquid Crystal Elastomer (LCE) rings that autonomously jump under uniform illumination, utilizing asymmetric heating and elastic storage to drive untethered, repeatable locomotion. Such systems are based on natural asymmetries and material instabilities and are used to transform energy inputs with uniform origin into a mechanical output with directional expansion.

Meanwhile, non-reciprocal active filaments extend this principle by incorporating pre-programmed buckling motifs along their longitudinal axis, enabling net displacement through cyclic morphological transitions. By breaking time-reversal symmetry, these systems demonstrate how precise geometric and material design can induce autonomous crawling or digging locomotion within confined environments, without external tethers or complex control.

Overall, such bio-inspired architectures go beyond static postural regulation to move towards functional competencies such as grasping, self-replication, locomotion, and rehabilitation. Their success speaks to the importance of multiscale inspirations ranging from cellular growth to avian biomechanics to design robust, energy-efficient, and scalable soft robotic platforms. This translation of bioinspired structural designs into real-world applications is evident in clinically validated systems. For instance, soft grippers based on glove technology, as shown in Figure 6, using mirrored motion systems have been created for hand rehabilitation in stroke and hemiplegia patients, where bilateral training was possible and holds promise for engagement in motor recovery [25].

Fig. 6. Soft robotic glove with mirroring system for hand rehabilitation: (a) relaxed hands and actuator alignment, (b) glove activation using pneumatic stands, (c) front view during actuation showing tightened-up hand posture. Reproduced from [25] under CC 4.0 licence [39].

Similarly, textile-based soft exosuits using fabric-type artificial muscles, as portrayed in Figure 7, have shown significant improvement in shoulder elevation and functional mobility in patients with neuromuscular disease with no side effects observed [26].

These examples underscore how biologically inspired morphology, actuation, and sensing can converge into clinically viable tools for improving mobility, autonomy, and quality of life for human users.

V. INTELLIGENT MODELING AND CONTROL STRATEGIES

Advances in modeling and control are transforming soft actuation from heuristic tuning into a predictive, optimization-based discipline. By combining analytical mechanics with data-driven learning, researchers are developing hybrid frameworks that enhance model accuracy, control efficiency, and real-time adaptability across different actuator types.

Fig. 7. Soft shoulder exosuit for assisting shoulder elevation in neuromuscular disorders: (a–b) vest-like wearable integrated with elastic straps and fabric-type artificial muscles for comfortable long-term use, (c) conceptual diagram showing contraction force and dual anchoring mechanism for shoulder motion assistance, (d) portable control system including the main board, current driver, and wireless smartphone interface. Reproduced from [26] under CC 4.0 licence [39].

Fluid-aware control architectures couple electrical and hydraulic dynamics to capture internal damping, fluid inertia, and leakage losses. Authors in [15] demonstrated the benefits of such integrated models to enhance the speed of actuation and reduce control noise compared to the more common decoupled approaches, particularly in dielectric elastomer and hydraulically amplified systems.

Sequence-based learning controllers, such as bidirectional Long-Short-Term Memory (biLSTM) networks, manage complex temporal input–output relationships. Authors in [27] used biLSTM controllers for modular soft robotic arms, achieving stable and precise control under changing morphologies and payloads, conditions in which classical controllers often fail due to parameter drift, hysteresis, and geometric nonlinearity.

To be able to deal with nonlinear system dynamics in a more interpretable way, Koopman-based predictive control has become a promising technique. This technique is used to lift the nonlinear behavior of systems into the linear observable space, where MPC techniques can be used inside the tractable region. Authors in [28] showed that Koopman-based MPC significantly outperformed traditional PID controllers in human–robot interaction tasks, especially in maintaining compliance and trajectory accuracy under unpredictable contact forces.

Beyond control, design optimization frameworks are being overturned using genetic algorithms and topological search methods. Author in [29] designed a genetic topology design pipeline to automate the actuator morphology generation based on the performance constraints, including the stroke amplitude, energy efficiency, and material limits, so that the time required for synthesis may be reduced from days to minutes.

To improve adaptability in uncertain environments, recent systems have introduced the use of real-time feedback loops, which combine proprioceptive sensing, data from the physical environment, and predictive models. This allows for closed-loop adaptation of the structure and behavior, which is crucial for operating in dynamic and unstructured environments or contact-rich environments [30].

At a higher abstraction level, multiscale modeling roadmaps now span molecular dynamics, mesoscale deformation mechanics, and full-system interactions. Authors in [17] proposed a hierarchical modeling framework that integrates quantum-informed polymer models with finite element and system-level dynamics, enhancing cross-domain predictability and enabling the simulation of novel material, structure, and control couplings.

Collectively, these hybrid modeling and control strategies mark a paradigm shift toward standardized digital twins, where real-time, simulation-informed controllers can iteratively refine both structural and behavioral parameters. This evolution supports intelligent co-design workflows, where actuator geometry, material properties, and control logic are co-optimized from concept to deployment, facilitating automation in the design, model, and test cycle.

VI. CURRENT LIMITATIONS AND CHALLENGES

Despite progress in soft actuation and bio-inspired design, several limitations still hinder the transition from lab prototypes to robust, deployable systems. One of the major problems is the absence of standardization of the testing protocols. Metrics, such as strain, force, work density, and efficiency, have inconsistent definitions and, therefore, cannot be compared between studies. Community-driven benchmarking platforms and open-access actuator repositories have been proposed to improve reproducibility [21].

Fatigue performance is often underreported, especially for electroactive materials such as dielectric elastomers and LCEs. Although many systems perform well in single-cycle tests, their long-term mechanical stability and degradation pathways remain unclear. High-throughput fatigue testing platforms, predictive lifespan models, and accelerated aging protocols are being developed to address this gap.

Fabrication reproducibility is another challenge. Manual assembly introduces variability in bonding and internal stresses, which reduces scalability. Modular microfabrication methods that are available, such as 3D printing, roll-to-roll casting, and digital light processing, improve consistency and still allow for design complexity [31]. In addition, manufacturing scalability is limited because of the use of manual or semi-automated processes. Scaling up production without degrading functionality or customization capability is an open problem. Cost is also a barrier, as many soft robotic materials, such as high-performance elastomers and embedded sensors, are expensive or require specialized equipment. Future directions should address cost-effective materials and scalable manufacturing workflows.

Trade-offs between hybrid and fully soft designs complicate actuator development. Rigid elements increase precision but may decrease compliance and safety. Computational co-design tools, such as topology optimization and sensitivity analysis, help quantify these trade-offs [32]. Modeling and control efforts are limited by nonlinearity, hysteresis, and material anisotropy. Hybrid physics-based and data-driven models hold promise but suffer from the issue of overfitting and the limitations of embedded systems. Uncertainty quantification methods, like Gaussian processes and Bayesian networks, offer robustness under sparse data [33], and neuromorphic or edge-computing architectures may support real-time adaptive control.

Addressing these challenges requires collective efforts toward protocol standardization, modular testbeds, and multi-scale modeling with uncertainty quantification to move soft actuation toward reproducible engineering.

VII. CONCLUSION AND ROADMAP FOR FUTURE DIRECTIONS

This review outlines the current state of the art in soft planar actuation, benchmarking metrics, and bio-inspired structural designs for soft robotics. Through a detailed comparative analysis of materials, architectures, and mechanisms, the diversity and adaptability of soft actuators to compliance-demanding tasks are emphasized. Benchmarking efforts in terms of strain, force density, efficiency, and durability are essential to enable meaningful comparisons across platforms and to support the selection of actuators for specific applications.

Bioinspired structural designs, from avian claws to tip-growing vines and origami exoskeletons, demonstrate how nature continues to inform actuation strategies that are both efficient and scalable. The current review highlights clinically validated systems, such as wearable exosuits and soft gloves, which demonstrate the practical translation of soft robotic principles into rehabilitation, assistive mobility, and therapeutic recovery.

Advancing soft planar actuation systems requires a structured roadmap across short-, mid-, and long-term goals. In the short-term goals, standardization of performance measures, like actuation strain, work density, and fatigue life, is critical. Creating open-access datasets of material properties, actuator behaviors, and control inputs will enable data-driven modeling efforts and data reproducibility [34]. Integrating stretchable sensors into actuators will allow real-time feedback on deformation, temperature, and load. These can be complemented with control strategies such as Model Predictive Control (MPC), reinforcement learning, and Koopman-based strategies for increased autonomy and safety in dynamic environments [30].

Early real-world prototypes are already emerging. For example, soft robotic gloves for stroke rehabilitation are undergoing clinical validation, combining planar actuators with assisting as-needed control [35]. Similarly, wearable textile-based exosuits have demonstrated metabolic cost reduction during walking trials [36], illustrating the translational potential of soft planar systems.

Long-term focus should shift to sustainability and scalability. Increased dependence on recyclable, biodegradable, or energy autonomous materials will minimize the impact on the environment. Biodegradable actuators and green elastomers are being designed to degrade safely at end-of-life without harmful residues [37]. At the same time, onboard power systems, like flexible photovoltaics, piezoelectric fabrics, and triboelectric generators, are advancing untethered operation [38].

Soft planar robots are ideal for rehabilitation, wearable assistance, adaptive infrastructure, and disaster response. Realizing their full potential requires continuous innovation and collaboration across materials, mechanics, control, and human-machine integration.

REFERENCES

[1] H. Jeong, J. Kim, and J. Paik, "Low-Profile Folding Mechanism for Multi-DoF Feedback Control," *Soft Matter*, vol. 21, no. 31, pp. 6186–6196, 2025, https://doi.org/10.1039/D5SM00143A.

[2] J. Joshi, A. R. Manral, and P. Kumar, "Technologies and Applications of Soft Robotics: A Review," *Journal of Graphic Era University*, Oct. 2023, https://doi.org/10.13052/jgeu0975-1416.1128.

[3] A. Saber, M. Al Sharah, Y. Al Tamimi, S. Amine, and E. Gazo Hanna, "Design, Dynamic Simulation, and Prototyping of a Dual-Axis Solar Tracker using a Slider-Crank Mechanism," *Engineering, Technology & Applied Science Research*, vol. 15, no. 5, pp. 26224–26230, Oct. 2025, https://doi.org/10.48084/etasr.12414.

[4] C. Aygül, C. Güven, S. A. Frunzi, B. J. Katz, and M. P. Nemitz, "A Framework for Soft Mechanism Driven Robots," *Nature Communications*, vol. 16, no. 1, Feb. 2025, Art. no. 1426, https://doi.org/10.1038/s41467-025-56025-3.

[5] S. Z. Ying, N. K. Al-Shammari, A. A. Faudzi, and Y. Sabzehmeidani, "Continuous Progressive Actuator Robot for Hand Rehabilitation," *Engineering, Technology & Applied Science Research*, vol. 10, no. 1, pp. 5276–5280, Feb. 2020, https://doi.org/10.48084/etasr.3212.

[6] S. Amine, M. T. Masouleh, S. Caro, P. Wenger, and C. Gosselin, "Singularity Analysis of the 4 RUU Parallel Manipulator Using Grassmann-Cayley Algebra," *Transactions of the Canadian Society for Mechanical Engineering*, vol. 35, no. 4, pp. 515–528, Dec. 2011, https://doi.org/10.1139/tcsme-2011-0031.

[7] D. Rus and M. T. Tolley, "Design, Fabrication and Control of Soft Robots," *Nature*, vol. 521, no. 7553, pp. 467–475, May 2015, https://doi.org/10.1038/nature14543.

[8] D. Trivedi, C. D. Rahn, W. M. Kier, and I. D. Walker, "Soft Robotics: Biological Inspiration, State of the Art, and Future Research," *Applied Bionics and Biomechanics*, vol. 5, no. 3, pp. 99–117, Jan. 2008, https://doi.org/10.1080/11762320802557865.

[9] W. Li, D. Hu, and L. Yang, "Actuation Mechanisms and Applications for Soft Robots: A Comprehensive Review," *Applied Sciences*, vol. 13, no. 16, Aug. 2023, Art. no. 9255, https://doi.org/10.3390/app13169255.

[10] P. Lloyd, O. Onaizah, G. Pittiglio, D. K. Vithanage, J. H. Chandler, and P. Valdastri, "Magnetic Soft Continuum Robots with Braided Reinforcement," *IEEE Robotics and Automation Letters*, vol. 7, no. 4, pp. 9770–9777, Oct. 2022, https://doi.org/10.1109/LRA.2022.3191552.

[11] W. Wang, F. Xi, Y. Tian, Y. Zhao, and Y. Li, "Modeling and Analysis of a Planar Soft Panel Continuum Mechanism," *Journal of Mechanisms and Robotics*, vol. 12, no. 4, Aug. 2020, Art. no. 044503, https://doi.org/10.1115/1.4046029.

[12] B. Mauze *et al.*, "Nanometer Precision with a Planar Parallel Continuum Robot," *IEEE Robotics and Automation Letters*, vol. 5, no. 3, pp. 3806–3813, Jul. 2020, https://doi.org/10.1109/LRA.2020.2982360.

[13] M. Li, A. Pal, A. Aghakhani, A. Pena-Francesch, and M. Sitti, "Soft Actuators for Real-World Applications," *Nature Reviews Materials*, vol. 7, no. 3, pp. 235–249, Nov. 2021, https://doi.org/10.1038/s41578-021-00389-7.

[14] N. El-Atab *et al.*, "Soft Actuators for Soft Robotic Applications: A Review," *Advanced Intelligent Systems*, vol. 2, no. 10, Oct. 2020, Art. no. 2000128, https://doi.org/10.1002/aisy.202000128.

[15] H. Meng, C. Zhou, X. Yang, P. Zhao, and W. Zhang, "Design and Control of a Novel Pneumatic Soft Robot based on the Improved Particle Swarm Optimization Algorithm," *PLOS One*, vol. 20, no. 9, Sept. 2025, Art. no. e0333187, https://doi.org/10.1371/journal.pone.0333187.

[16] A. M. R. Abolhosen, S. Lee, K. Fukuda, T. Someya, L. H. González, and J. Shintake, "Functional Soft Robotic Composites based on Organic Photovoltaic and Dielectric Elastomer Actuator," *Scientific Reports*, vol. 14, no. 1, Apr. 2024, Art. no. 9953, https://doi.org/10.1038/s41598-024-60899-6.

[17] H. Li, B. Li, P. Zhou, Z. Lin, X. Li, and J. Yao, "Variable Stiffness Woven Soft Active Textiles and Robots using Thin McKibben Muscle," *Soft Robotics*, Oct. 2025, Art. no. 21695172251379609, https://doi.org/10.1177/21695172251379609.

[18] S. Huang *et al.*, "Hybrid Pneumatic-Hydraulic Actuation for MRI-Guided Robotic Stereotactic Neurointervention," *Science Advances*, vol. 11, no. 36, Sept. 2025, Art. no. eady3624, https://doi.org/10.1126/sciadv.ady3624.

[19] K. Fu *et al.*, "Origami Exoskeletons for Enhanced Soft Robotic Manipulation," *Science Advances*, vol. 11, no. 31, Aug. 2025, Art. no. eadv6629, https://doi.org/10.1126/sciadv.adv6629.

[20] K. Karunakaran, V. Ebenezer, V. Vijayaragavan, K. Kesavan, J. Bhuvaneshwarri, and R. Thilakavathi, "Biocompatible Soft Robotics: Integrating Smart Materials for Biomedical Innovation," in *6th International Conference in Robotics and Manufacturing Automation*, Selangor, Malaysia, Aug. 2025, pp. 29–33, https://doi.org/10.1109/ROMA66616.2025.11155352.

[21] L. Rupert, B. O. Saunders, and M. D. Killpack, "Performance Metrics for Fluidic Soft Robot Rotational Actuators," *Frontiers in Robotics and AI*, vol. 8, Aug. 2021, Art. no. 632835, https://doi.org/10.3389/frobt.2021.632835.

[22] O. Perera, R. Liyanapathirana, G. Gargiulo, and U. Gunawardana, "A Review of Soft Robotic Actuators and Their Applications in Bioengineering, with an Emphasis on HASEL Actuators' Future Potential," *Actuators*, vol. 13, no. 12, Dec. 2024, Art. no. 524, https://doi.org/10.3390/act13120524.

[23] M. E. Stokes, J. K. Mohrmann, C. G. Frazelle, I. D. Walker, and G. Lv, "The Claw: An Avian-Inspired, Large Scale, Hybrid Rigid-Continuum Gripper," *Robotics*, vol. 13, no. 3, Mar. 2024, Art. no. 52, https://doi.org/10.3390/robotics13030052.

[24] A. Astar, O. Nurcan, E. Demirel, E. Ozen, O. Kutlar, and F. Stroppa, "Design Optimizer for Soft Growing Robot Manipulators in Three-Dimensional Environments." arXiv, Jan. 23, 2025, https://doi.org/10.48550/arXiv.2501.00368.

[25] H. D. Bryantono, C.-Y. Su, J.-K. Huang, T.-W. Xin, and S.-C. Tseng, "Soft Gripper Gloves with Mirroring System Design for Hand Rehabilitation," in *8th Eurasian Conference on Educational Innovation 2025*, Bali, Indonesia, Sept. 2025, Art. no. 29, https://doi.org/10.3390/engproc2025103029.

[26] S. J. Park *et al.*, "Soft Exosuit Based on Fabric Muscle to Assist Shoulder Joint Movements in Patients with Neuromuscular Diseases," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 33, pp. 3866–3877, 2025, https://doi.org/10.1109/TNSRE.2025.3613709.

[27] Z. Chen, M. Bernabei, V. Mainardi, X. Ren, G. Ciuti, and C. Stefanini, "A Novel and Accurate BiLSTM Configuration Controller for Modular Soft Robots with Module Number Adaptability," *Soft Robotics*, Dec. 2024, Art. no. soro.2024.0015, https://doi.org/10.1089/soro.2024.0015.

[28] Z. Gu *et al.*, "Humanoid Locomotion and Manipulation: Current Progress and Challenges in Control, Planning, and Learning." arXiv, Apr. 19, 2025, https://doi.org/10.48550/arXiv.2501.02116.

[29] J. Zou, "Multi-Scale Incremental Modeling for Enhanced Human Motion Prediction in Human-Robot Collaboration." arXiv, Dec. 16, 2024, https://doi.org/10.48550/arXiv.2412.11632.

[30] Z. Chen *et al.*, "Data-Driven Methods Applied to Soft Robot Modeling and Control: A Review," *IEEE Transactions on Automation Science and Engineering*, vol. 22, pp. 2241–2256, 2025, https://doi.org/10.1109/TASE.2024.3377291.

[31] F. Stroppa, F. J. Majeed, J. Batiya, E. Baran, and M. Sarac, "Optimizing Soft Robot Design and Tracking with and Without Evolutionary Computation: An Intensive Survey," *Robotica*, vol. 42, no. 8, pp. 2848–2884, Aug. 2024, https://doi.org/10.1017/S0263574724001152.

[32] L. Li *et al.*, "A Comparative Analysis and Scoping Review of Soft–Rigid and Industrial Parallel Rigid Grippers," *Advanced Intelligent Systems*, vol. 7, no. 5, May 2025, Art. no. 2400503, https://doi.org/10.1002/aisy.202400503.

[33] L. Qin, H. Peng, X. Huang, M. Liu, and W. Huang, "Modeling and Simulation of Dynamics in Soft Robotics: A Review of Numerical Approaches," *Current Robotics Reports*, vol. 5, no. 1, pp. 1–13, Aug. 2023, https://doi.org/10.1007/s43154-023-00105-z.

[34] O. Yasa *et al.*, "An Overview of Soft Robotics," *Annual Review of Control, Robotics, and Autonomous Systems*, vol. 6, no. 1, pp. 1–29, May 2023, https://doi.org/10.1146/annurev-control-062322-100607.

[35] P. Polygerinos, K. C. Galloway, E. Savage, M. Herman, K. O. Donnell, and C. J. Walsh, "Soft Robotic Glove for Hand Rehabilitation and Task Specific Training," in *2015 IEEE International Conference on Robotics and Automation*, Seattle, WA, USA, May 2015, pp. 2913–2919, https://doi.org/10.1109/ICRA.2015.7139597.

[36] F. A. Panizzolo *et al.*, "A Biologically-Inspired Multi-Joint Soft Exosuit that can Reduce the Energy Cost of Loaded Walking," *Journal of NeuroEngineering and Rehabilitation*, vol. 13, no. 1, Dec. 2016, Art. no. 43, https://doi.org/10.1186/s12984-016-0150-9.

[37] Y. Xie *et al.*, "A Review on Biodegradable Materials of Sustainable Soft Robotics and Electronics," *Advanced Science*, Aug. 2025, Art. no. e10320, https://doi.org/10.1002/advs.202510320.

[38] G. Giordano, S. P. Murali Babu, and B. Mazzolai, "Soft Robotics Towards Sustainable Development Goals and Climate Actions," *Frontiers in Robotics and AI*, vol. 10, Mar. 2023, Art. no. 1116005, https://doi.org/10.3389/frobt.2023.1116005.

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