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Advances in Soft Robotics: Emerging Paradigms for Bodyware and Control

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***Abstract*— Over the past five decades, robotics has achieved remarkable progress, grounded in the foundational assumption that robotic systems are composed of interconnected rigid links. However, the emerging integration of soft materials—motivated by new scientific paradigms such as biomimetics and morphological computation, as well as a growing range of applications including biomedical devices, service robots, and search-and-rescue technologies—is challenging this traditional framework. As a result, many established theories and methodologies have become inadequate, paving the way for innovative approaches to robot design and control.**

Current developments in soft robotics encompass diverse strategies for actuation and control. Although these advancements are still in the early stages, they hold significant potential to drive transformative technological change. Soft robotics represents more than an incremental development; it embodies a fundamental rethinking of robotics, reshaping long-standing principles and enabling the creation of a new generation of robots capable of interacting seamlessly with humans and operating effectively within natural environments.

***Index Terms* — soft robotics, morphological computation, biomimetic robotics, biorobotics, smart materials.**

I. THE SOFT ROBOTICS CHALLENGE

In the near past, robotics has advanced at an exceptional pace, resulting in highly mature technologies capable of delivering precise, rapid, and reliable motion control. The extensive body of knowledge developed during this period—spanning robot control, fabrication, and sensing—has been built upon a foundational assumption: robots are composed of kinematic chains formed by rigid links. This conventional definition has shaped nearly all existing theories and methodologies in the field. Recent progress in soft and smart materials, compliant mechanisms, and nonlinear modeling has significantly expanded the use of soft materials in robotics across the globe. This trend is driven not only by emerging scientific frameworks—such as biomimetics and morphological computation—but also by practical demands from various application domains, including biomedical devices, service robotics, and search-and-rescue systems. Soft robots are increasingly favored for their ability to interact more naturally, safely, and effectively with complex real-world environments (Mazzolai et al., 2012; Pfeifer et al., 2012). Within biomimetics, the adoption of soft materials is inspired by countless biological exemplars found in both animal and plant systems. Even organisms with rigid internal or external skeletons rely extensively on soft tissues. These tissues enable variable material properties—such as stiffness, elasticity, and surface texture—support muscle-driven motion, and facilitate sensing through skin-embedded mechanoreceptors (Kim et al., 2013).

Compliance or softness is also essential for realizing the principles of embodied intelligence or morphological computation, contemporary frameworks that emphasize the critical role of a system's physical body and its interactions with the environment. Current perspectives in robotics suggest that fast, efficient, and robust behaviors can be achieved by strategically leveraging material properties, particularly softness (Pfeifer et al., 2012). Soft materials are therefore viewed as key enablers for automating tasks that lie beyond the capabilities of traditional rigid robots. The significance of soft structures is evident throughout nature, where they contribute to adaptability and resilience. For instance, human skin is soft, deformable, and highly durable—remaining both robust and waterproof—while playing a vital role in grasping, manipulation, and tactile sensing. The integration of soft, deformable, and variable-stiffness technologies in robotics represents a rapidly emerging strategy for developing new classes of robots capable of interacting more safely with unstructured natural environments and with humans. Such systems are better suited to handle uncertain and dynamic tasks, including grasping and manipulating unfamiliar objects (Brown et al., 2010), navigating uneven terrain (Lin et al., 2011), and engaging in physical contact with human bodies.

As the field of soft robotics continues to expand globally, it is important to distinguish between two primary approaches to achieving compliant interaction:

(1) modulating actuator stiffness in robots constructed with rigid links (Albu-Schäffer et al., 2008), and

(2) leveraging the inherent softness arising from the passive material properties of the robot's bodyware (Trivedi et al., 2008). In the first approach, robots retain conventional rigid-link structures, but their control systems modulate the resistance exhibited during interactions with the environment—whether with objects or humans—using compliance or impedance control strategies (Siciliano and

Villani, 1999). In rehabilitation settings, for example, physical therapy robots employ interaction-control schemes that adjust their stiffness in response to the forces exerted by patients (Krebs et al., 2000).

Within this same framework, actuators are engineered to possess adjustable impedance. These variable impedance actuators (VIA) are capable of altering their output stiffness independently of their output position, enabling more adaptable and safer interactions (Vanderborght et al., 2009; Visser et al., 2011). In the second approach, robots are constructed entirely from soft materials, allowing them to undergo substantial deformation during interaction. This method relies on soft actuators and materials capable of varying stiffness, with elements of control embedded directly within the robot's physical morphology. By leveraging the inherent properties of these materials, the robot can naturally adapt its behavior to environmental conditions (Brooks, 1991; Pfeifer and Bongard, 2007). Soft-bodied robots can sustain significant deformation under normal loading and utilize passive body compliance to conform to their surroundings (Brown et al., 2010). Consequently, tasks traditionally handled by complex control systems can be partially offloaded to the mechanical characteristics of the robot's body (Pfeifer and Bongard, 2007). The primary advantage of this strategy is the potential to simplify control architectures by using highly compliant, variable-stiffness materials that inherently contribute to task execution. Interaction with objects and environments becomes a function of the robot's physical adaptability, forming the foundation of Morphological Computation.

In this context, soft robotics refers specifically to this second paradigm: the use of soft materials and mechanisms that enable dynamic changes in body shape and stiffness. This represents a fundamentally transformative shift, as it departs from the traditional assumptions of rigid-link robotics. As a result, many established theories and methodologies in robotics become insufficient, necessitating new design and control solutions.

The following sections outline key challenges in soft robot design and control, highlight promising technological approaches, and present potential strategies for advancing this emerging field.

II. SMART ACTUATORS AND MANUFACTURING TECHNOLOGIES FOR SOFT ROBOTS

Within the field of soft robotics, one of the most significant challenges lies in the limited availability of reliable and robust soft actuators. Despite this bottleneck, several promising technologies are rapidly emerging and drawing the attention of a growing number of research groups. Advances in smart materials—characterized by their inherent softness and flexibility—are poised to form the next frontier in the development of high-performance soft actuators.

Shape Memory Alloys (SMAs) are metallic alloys that can undergo significant deformation and subsequently return to their original shape upon heating. Their use enables substantial reductions in the size, weight, and complexity of robotic systems. Owing to their high force-to-weight ratio, long operational life, minimal volume, inherent sensing capabilities, and silent operation, SMAs are well-suited for applications in soft robotics (Cianchetti, 2013). However, they typically require relatively high electrical currents and exhibit low energy efficiency. Additionally, the pronounced nonlinearity and hysteresis associated with their activation make precise control challenging. Many of these limitations can be mitigated through the use of Shape Memory Polymers (SMPs), which operate on the same underlying mechanism as SMAs but respond to alternative activation stimuli beyond electrical input. Triggering can be achieved through chemical or thermal inputs, as well as through light or magnetic fields—methods that often provide improved transduction efficiency, though typically at the expense of slower response times. SMPs are classified within the broader family of smart polymers and have attracted significant research attention in recent years due to their promising use in micro-electromechanical systems and biomedical actuator technologies. In numerous application domains, SMP materials have demonstrated effectiveness as alternatives to metal-based counterparts, owing to their adaptability, biocompatibility, and extensive possibilities for property tuning. A detailed overview of this subject is provided in the review by Ratna and Karger-Kocsis (2008). Electroactive Polymers (EAPs) represent a rapidly developing and highly promising technological class, already showing potential to bridge the performance gap between biological and synthetic muscle systems. While various activation mechanisms exist, most EAPs are derived from polymer-based matrices and share the ability to undergo dimensional and shape changes in response to an applied electrical stimulus (Mirfakhrai et al., 2007). These materials offer power densities surpassing those of natural muscle, are scalable in design, compatible with free-form fabrication, and well-suited for biomimetic and biomedical soft robotics. However, depending on the particular type of EAP employed, limitations such as slow actuation speed or the requirement for high operating voltages may restrict their applicability. Further advancements in durability and operational reliability are also necessary. The term 'flexible fluidic actuator' encompasses a broad array of system configurations, though they typically consist of an expansion chamber bounded by an internal compliant girdle and anchored at a minimum of two fixed points. This structure allows the actuator to convert fluid pressure exerted on the chamber's inner surface into either tensile output or bending deformation. Pneumatic variants operate as contractile, linear-motion actuators driven by compressed gas. While they can deliver high power density, their dependence on large fluid supply units imposes bulkiness and restricts the extent of miniaturization. A detailed overview of this technology is provided in De Greef et al. (2009).

Cable-driven actuation offers the advantage of delivering distributed and continuous motion, with cables easily routed through regions of a soft robot where integrating other actuators would be difficult. Because the primary motors can be positioned externally, the robot remains lightweight and flexible. The continuous nature of cable transmission, combined with minimal backlash, simplifies control; however, friction losses along the cable path can diminish controllability. Relative to other actuation strategies, cable-based systems provide low inertia, reduced weight and volume, rapid response characteristics, and efficient long-distance transmission of force and power. Beyond fully active actuation mechanisms, certain smart materials have been utilized as semi-active actuators—systems capable only of dissipating energy during mechanical interaction. This category of materials enables modulation of mechanical properties through controlled external stimuli. Thermo-, magneto-, and electro-rheological materials, for instance, can shift their stiffness from that of a low-viscosity fluid to values comparable to solid matter when subjected to thermal, magnetic, or electric fields, respectively. However, these technologies face notable limitations, including complex control requirements and slow response under thermal activation, as well as the need for high magnetic or electric field intensities. Other than active actuators, certain smart materials have been employed as semi-active actuators, meaning they can only dissipate energy during mechanical interaction. This distinct material class allows modulation of mechanical properties in response to controlled physical stimuli. Thermo-, magneto-, and electro-rheological materials, for example, can alter their stiffness from levels comparable to low-viscosity fluids to those resembling solid matter when exposed to thermal, magnetic, or electric fields. Despite these advantages, their use is constrained by control challenges and relatively slow response times for thermal activation, as well as the need for high field strengths in magnetically or electrically driven systems. Granular jamming is another increasingly studied phenomenon, notable for its remarkable ability to make particulate matter behave like a liquid, a solid, or an intermediate state depending on the applied vacuum level. While material development and actuation technologies remain central to soft robotics research, the fabrication of such systems presents an equally significant challenge. Emerging manufacturing techniques, such as Shape Deposition Manufacturing (SDM) and Smart Composite Microstructures (SCM), have been introduced to address this need. However, despite the rising interest in the field, only a limited number of existing soft robots fully meet the adopted definition of soft robotics, and most incorporate only a few of the aforementioned components.

III. ARCHITECTURES AND CONTROL PARADIGMS IN SOFT ROBOTICS

As noted earlier, traditional robot control theories and methods are not well suited to systems constructed from soft materials, which typically behave as continuum structures. Most existing approaches for direct modeling of soft continuum robots rely on the piecewise constant curvature approximation. Jones et al. (2009) introduced a steady-state model for continuous robots, but without accounting for actuation. Similarly, Boyer et al. (2006) estimated distributed forces and torques along the robot body, though the work did not address the types of actuators capable of generating those loads.

A geometrically exact continuum formulation for tendon-driven manipulators was later developed by Renda et al. (2012), enabling accurate simulation of coupled tendon dynamics in non-constant curvature structures by incorporating torsional effects. Wittmeier et al. (2013) evaluated six distinct control strategies—spanning classical control, machine learning, and neuroscience-inspired approaches—on a cable-driven soft robot. Inverse modeling strategies for controlling soft continuum robots also vary considerably. A modal formulation was introduced by Chirikjian and Burdick (1994), while Giorelli et al. (2012) presented a Jacobian-based solution that proved effective for controlling a tendon-driven manipulator with non-constant curvature. Conversely, the principles of embodied intelligence and morphological computation offer promising pathways for controlling soft robots. Here, control is achieved by leveraging the robot’s physical interaction with its environment rather than relying solely on analytical modeling. Instead of explicitly formulating the complex dynamics of soft–environment interaction, internal models are developed through experiential learning in the real world, analogous to how the brain forms internal representations. These models capture correlations between sensory feedback and motor commands, effectively encoding the portion of control inherently performed by the robot’s body interacting with its surroundings—referred to as morphological computation. In this framework, soft computing techniques play a central role, with particular emphasis on self-organizing neural network architectures capable of autonomously extracting and structuring these relationships. Recently, neural network–based methods have been applied to continuum robots for mapping actuator inputs to resulting manipulator configurations. Notably, Giorelli et al. (2013) conducted a comparative study between a neural network controller and an inverse Jacobian–based controller for a soft robotic arm. Their results demonstrated that the neural approach effectively accommodates variations in the arm’s morphology without degrading control performance, highlighting its robustness in scenarios where mechanical properties may change over time or under different operating conditions.

IV. THE EMERGENCE OF SOFT ROBOTICS: EARLY CONCEPTS AND PROGRESS

At Harvard University, a number of pneumatically actuated soft robots have been developed, including starfish-like forms (Shepherd et al., 2011) and tentacle-inspired designs (Martinez et al., 2013) illustrated in Figure 1. These systems exhibit extensive deformation capabilities as well as adaptive camouflage. In both cases, limb articulation is driven by a single pressure source, with motion determined by the geometry, layout, and channel dimensions of the embedded pneumatic networks. Among the other silicone- based soft robots, it is worth mentioning the soft caterpillar robot inspired by the Manduca sexta, the GoQBot, where SMA actu- ators and the incompressibility of fluids is exploited to deliver performance resembling those of the hydrostatic skeletons (Trim- mer et al., 2006; Lin et al., 2011) and the octopus-inspired robots developed at Scuola Superiore Sant'Anna, where the combination of soft materials and cable-driven transmission enabled manipulation capabilities (Cianchetti et al., 2011), legged locomotion (Calisti et al., 2011), and swimming (Giorgio Serchi et al., 2013).

Figure 1. Pneumatic tentacle-like soft manipulator (Martinez et al., 2013) (reproduced with permission from John Wiley and Sons).

Figure 2. Flexible octopus-like robot arm, composed by a braided sheath actuated by SMA springs (photo by Massimo Brega, The Lighthouse).

The JamBots (Steltz et al., 2010) demonstrate how soft materials, coupled with compliant actuation strategies, can enable effective locomotion and grasping. By exploiting granular jamming, their material stiffness can be altered to create directional anisotropies, while movement is produced through either pneumatic actuation or cable-driven mechanisms, as exemplified by the MIT jammable manipulator (Cheng et al., 2012). Soft materials may also serve as active components within the actuation system itself, as shown in the starfish-inspired robot driven by electroactive polymers (Otake et al., 2002) and the tissue-engineered, multi-appendage medusoid robot developed by Nawroth et al. (2012). Robots that leverage flexible structural elements are classified as soft systems because they rely on antagonistic actuation and the intrinsic elasticity of their constituent materials. A representative example is the Meshworm robot, which generates peristaltic locomotion through a sequence of shape-memory alloy (SMA) springs arranged antagonistically and housed within a compliant braided mesh tube (Seok et al., 2012). Another notable case is the octopus-inspired robotic arm, which achieves dexterous manipulation through artificial muscular hydrostats composed of a conically braided sheath that functions both as the arm's body and as the structural support for the SMA actuator network (Laschi et al., 2012), illustrated in Figure 2. Although soft robotics remains an emerging discipline and many existing prototypes address narrow, application-specific functions, the field is steadily generating a suite of technologies that may serve as foundational components for future robotic systems. Soft robotics represents more than a new technological trajectory—it introduces a fundamentally different paradigm that challenges conventional robotic principles. With continued progress, it holds the promise of enabling a new generation of machines capable of interacting safely, adaptively, and seamlessly within human environments.

V. THE ROLE OF SOFT ROBOTIC TECHNOLOGIES AND GRF ESTIMATION IN ADVANCED FOOT-DROP ASSIST SYSTEMS

The principles highlighted in the soft robotics literature are directly relevant to the development of a foot-drop rehabilitation system, where safe human–robot interaction, adaptability, and compliant motion are essential. Soft robotic actuators—particularly flexible fluidic and cable-driven mechanisms described in the document—offer the ability to mimic natural muscle behavior through controlled deformation, tunable stiffness, and embodied intelligence, making them ideal for assisting ankle dorsiflexion without imposing rigid constraints on the patient's limb. Such compliance is crucial in gait rehabilitation, where the device must continuously adapt to variable loading conditions during heel strike, foot-flat, and toe-off phases. Accurate estimation of ground reaction forces further enhances this framework by allowing the soft robotic system to modulate assistance in real time, ensuring stability, preventing over-correction, and enabling personalized therapeutic interventions. Integrating soft-actuator technology with GRF-driven control thus provides a safer, more biomimetic, and responsive solution for foot-drop correction during walking.

The concepts presented in the soft robotics paper are highly relevant to developing an advanced foot-drop rehabilitation system, as they emphasize compliant, safe, and adaptive interaction between robotic devices and the human body. Soft actuators—such as flexible fluidic, cable-driven, and variable-stiffness mechanisms—are specifically highlighted for their ability to mimic natural muscle behavior, deform safely under load, and adjust stiffness during interaction, making them ideal for assisting impaired ankle dorsiflexion during gait. These characteristics are essential in foot-drop therapy, where the device must support the foot during swing, tolerate ground impact at heel strike, and adapt to changing gait dynamics. Furthermore, the principles of morphological computation and embedded sensing described in the paper support the integration of ground reaction force estimation, enabling the soft robotic system to learn from physical interaction and modulate assistance in real time. Accurate GRF estimation is crucial for timing dorsiflexion support, preventing foot slap, and ensuring stable and symmetrical gait retraining. Thus, the paper's soft-robotic paradigms directly inform the design of a safer, more responsive, and human-compatible foot-drop rehabilitation system.

Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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