

Flexible Sensing-based Soft Robotics: Key Technology and Applications in Medical Rehabilitation

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Abstract. Medical rehabilitation is being revolutionized by the integration of soft robotics and flexible sensing technologies, which overcome critical limitations of traditional rigid robots—such as safety risks, discomfort, and limited adaptability. This synergy enables high-precision monitoring of physiological and kinematic signals—including pressure, strain, biochemical, and temperature metrics—through resistive, capacitive, and piezoelectric sensing mechanisms. By combining innovative materials with optimized algorithms, integrated drive-sensing-control systems have been developed to support closed-loop, personalized therapy. Notably, wearable devices such as smart gloves and exosuits have demonstrated significant improvements in hand function recovery, gait training, and respiratory assistance for patients with stroke or Parkinson’s disease. Looking forward, advances in self-healing materials, digital twin technology, and AI-driven adaptation are poised to enable highly customizable rehabilitation and scalable home-based care, offering a transformative pathway for intelligent, user-centered medical recovery. This article aims to provide a systematic reference and research direction for the deep integration of soft robots and flexible sensing technology in the field of medical rehabilitation, and to promote the development of intelligent, personalized and sustainable rehabilitation solutions.

Keywords: Soft robotics, Flexible sensing, medical rehabilitation, Wearable devices.

1. Introduction

The growing global population aging and the rising incidence of neurological disorders have led to a surge in demand for medical rehabilitation since the start of the 21st century [1]. A majority of stroke survivors experience persistent impairments such as hand dysfunction, underscoring the urgent need for effective rehabilitation therapies. For decades, the field of rehabilitation medicine has depended on traditional rigid robots to support patient recovery. Although these systems are useful for delivering repetitive, high-intensity training, their drawbacks are increasingly evident. Built from metals, hard plastics, or carbon fiber, rigid robots tend to be bulky and heavy. This can cause patient discomfort and may even lead to secondary injuries due to unwanted pressure or restricted joint mobility. More importantly, the rigid linkages often malposition with the natural rotation centers of human joints. Such kinematic mismatch compels patients to adjust their movement patterns, resulting in compensatory fatigue and diminished rehabilitation outcomes [2].

Safety is another concern: rigid exoskeletons operating in pure position control mode follow predefined trajectories that lack adaptability. This inflexibility can delay response to changes in patient status, increasing the risk of rigid-impact incidents [3]. Furthermore, high costs and short battery life limit their widespread adoption [2]. In response, the combination of flexible sensing and soft robotics has created new opportunities in rehabilitation. Using compliant materials, soft actuators, and intelligent control systems, soft robots conform more naturally to the human body, supporting safer, more comfortable, and highly personalized rehabilitation. Advances in flexible sensors—including so-called “electronic skin” that detects pressure, bending, and stretch—have enabled soft robots to mimic human tactile perception, forming the foundation for more responsive and secure human-robot interaction.

This review systematically examines the integration of flexible sensing technologies with soft robotics for medical rehabilitation. It begins by analyzing core flexible sensing technologies (including pressure, strain, biochemical, and temperature sensors) and their working principles. It

then explores integration strategies across materials, structures, and system algorithms that enable closed-loop control and intelligent rehabilitation. Furthermore, the review investigates specific application scenarios, such as wearable rehabilitation training robots and smart prosthetic devices, highlighting their impact on hand function recovery, gait assistance, and respiratory rehabilitation for patients with stroke, spinal cord injuries, or Parkinson's disease. Finally, the review discusses current challenges and future directions, including the development of self-healing materials, digital twin technology, and AI-driven adaptation, which promise to advance soft robots toward more intelligent and personalized rehabilitation therapies. By synthesizing these aspects, this review aims to provide a comprehensive reference for further research and clinical translation in this rapidly evolving field.

2. Flexible Sensing Technologies of Soft Robots

The high degrees of freedom and flexibility of soft robots enhance their deformation capabilities, yet pose significant challenges for sensor development. Due to the substantial difference in elastic modulus between soft and rigid materials, traditional rigid sensors struggle to be directly applied in soft robotics [4]. By detecting changes in physical or chemical parameters, flexible sensors provide multi-dimensional environmental perception capabilities, which are crucial for achieving precision medical rehabilitation. In medical rehabilitation scenarios, the integration of various sensor types enables soft robots to simulate human tactile perception, motion sensing, and physiological monitoring functions, thereby improving the personalization and safety of rehabilitation training.

2.1. Pressure Sensor

Pressure sensors are core components enabling force feedback and safety in soft robotics, simulating human skin's tactile functions through pressure detection. Those kinds of sensors operate based on capacitive, piezoresistive, or piezoelectric principles: when external pressure acts on the sensor, internal electrical parameters (e.g, capacitance, resistance) change, allowing quantification of pressure values. For instance, capacitive tactile sensors utilize electrode spacing variations to alter capacitance values, boasting high sensitivity up to 52, 260.2 kPa⁻¹ and rapid response within 12 milliseconds. Piezoresistive sensors detect pressure through resistance changes in conductive materials under compression, making them more suitable for large-area deployment.

2.2. Strain Sensor

Strain sensors detect the motion status and joint angles of soft robots by monitoring their own deformation, with their working mechanism primarily relying on changes in resistance or inductance. When the sensor is stretched or bent, the geometric structure of conductive materials changes, altering resistance values, or magnetic components shift, causing inductance fluctuations. This converts deformation into electrical signals [5, 6]. Beijing University of Chemical Technology's MXene hydrogel-based epidermal sensors have achieved remarkable results in detecting relative resistance changes under both minor and major strains, and this sensor can monitor injured joints at various bending angles and provide potentially important diagnostic information for postoperative rehabilitation exercises [7]. The PPM@C-DES hydrogel sensor, can also assist in speech rehabilitation by monitoring vocal cord vibrations [8].

2.3. Biochemical Sensor

Biochemical sensors extend the capabilities of soft robotics from physical assistance to physiological parameter monitoring, enabling real-time detection of chemicals or biomarkers in bodily fluids or tissues. These sensors typically operate on electrochemical or optical principles, detecting target substances through signal changes generated by specific recognition elements (such as enzymes or antibodies) binding to them [5]. In medical rehabilitation, biochemical sensors can be used to monitor wound healing-related biomarkers such as pH value and glucose level, as well as electrolytes and drug concentration in sweat, providing molecular information for chronic disease

management and rehabilitation progress evaluation. The MXene-based hydrogel sensors developed at Beijing University of Chemical Technology not only monitor electrophysiological signals, but also accelerate wound healing through localized application [7]. Recent innovations include wearable electrochemical sensors for sweat detection patches and multifunctional integrated systems. The key challenges lie in enhancing selectivity and anti-contamination performance, while further research is required to address limitations in sensitivity and selectivity.

2.4. Temperature Sensor

Temperature sensors are used to evaluate inflammatory responses, circulatory status, and treatment efficacy during rehabilitation. Flexible temperature sensors, which are based on thermistors or thermoelectric effects, are made of polymer substrates combined with carbon nanomaterials, and have good ductility and measurement accuracy [9]. Inspired by plants, a soft robot developed by Southeast University can use the rheology of liquid metal to sense environmental changes, including temperature [9]. A flexible temperature sensor based on PEDOT: PSS+GO composite material was developed by Krishnan and colleagues at the Bhopal campus of the Indian Institute of Science Education and Research. The sensor was fabricated on a PET substrate and encapsulated with a nitrile rubber sheet, with its resistance variations measured using a Keysight DMM6500 digital multimeter [10].

3. Integration Strategy of Soft Robot and Flexible Sensing Technology

The deep integration of flexible sensing technology with soft robotics is the key to enhancing the performance of medical rehabilitation robots. Through collaborative innovation across three dimensions—materials, structures, and system algorithms—the development of a closed-loop intelligent rehabilitation system that integrates "sensing, decision-making, and action" has been achieved, providing patients with safer, more precise, and personalized rehabilitation experiences.

3.1. Material Integration

Material integration serves as the foundation for achieving compatibility between flexible sensors and soft robotics in terms of material mechanics and signal stability. Traditional "additive" integration methods face challenges such as mismatched interfacial stress and significant signal interference, while emerging material-level integration strategies have achieved integrated sensing and actuation through the development of intrinsically flexible conductive composites. The team led by Fengxin Sun at Jiangnan University has developed a woven pneumatic soft robot that employs innovative fabric programming design. Using industrial weaving technology, the sensor functions are directly integrated into the textile structure of the robot. This innovative technique employs low-elasticity polyester yarns as warp threads to ensure structural stability, while utilizing high-elastic spandex core yarns as weft threads to enable directional deformation. The fabric structure incorporates strain-sensing yarns woven from silver threads. This material-level integration eliminates interface stress incompatibility issues caused by traditional bonding and coating methods, achieving seamless integration of actuation and sensing capabilities [2].

The liquid metal-silicone ink of another breakthrough in material integration. By introducing vinyl silicone oil and platinum catalysts, the team overcame the high surface tension challenge of pure liquid metal, creating conductive ink with catalytic diffusion effects. During printing, the catalyst diffuses outward, curing the surrounding silicone gel to achieve self-encapsulation of liquid metal wires. This single-step process integrates sensor electrode layers and functional layers, providing an ideal material platform for integrated actuator-sensor soft robotics [11]. The "homogeneous device structure" design concept from the perspective of interface mechanical matching. Unlike traditional multi-layer heterostructures, their developed electronic skin features quasi-homogeneous composition and interconnection interfaces. Through microstructural interface topological cross-linking, the system achieves remarkable interface toughness of approximately 390 J m^{-2} and high

shear strength of 90 kPa. Remarkably, it maintains stable sensing performance even after 100,000 cycles of cyclic friction, effectively addressing the interface mismatch challenge between flexible sensors and soft robotics [12].

3.2. Integration at the Structural

Structural integration focuses on the spatial configuration and mechanical coupling of sensors in soft robotics. Different integration strategies directly impact the robot's sensing performance, motion flexibility, and system reliability. Based on the structural relationship between sensors and the robot's body, two primary strategies can be identified: distributed integration and internal embedded integration.

3.2.1. Distributed Integration

Distributed integration involves deploying sensor networks across the surface of soft robots or specific functional areas, forming multi-node sensing arrays to capture spatial information such as overall deformation and external force distribution. This strategy mimics the distribution of receptors in biological skin, providing rich environmental interaction data.

The printed human-machine interface developed by the ShanghaiTech University team exemplifies distributed integration. Utilizing printing technologies including direct ink writing, infrared laser engraving, and laser cutting, the system fabricates circuit lines measuring just 40 micrometers in width on flexible substrates, forming high-density sensor arrays. This distributed electronic skin can be attached to robotic surfaces to monitor various physiological signals in real time, such as surface electromyographic signals and tactile pressure distribution. Through machine learning algorithms, it achieves gesture recognition and material identification [13].

Harvard University's soft robotic suit for Parkinson's rehabilitation employs a distributed integration strategy. The system features multiple flexible sensor nodes strategically placed around the hips and thighs, which use algorithms to estimate gait phases and generate assistive forces synchronized with muscle movements. This distributed sensing network comprehensively monitors patients' motion patterns, providing comprehensive data support for interventions targeting freezing gait [14].

3.2.2. Internal Embedded Integration

Internal embedded integration involves embedding sensors within soft robot structures to achieve deep coupling between body perception and actuators. This strategy protects sensors from external environmental interference while enabling precise monitoring of internal states. Jiangnan University's woven pneumatic soft robot incorporates strain-sensing yarns directly into its structure, forming a symbiotic sensing system with the actuation mechanism. When actuators deform through inflation, the embedded yarns deform accordingly, reflecting real-time bending status via resistance changes. This self-sensing capability eliminates the need for external sensors [2].

The bionic robotic fish developed by the Shenyang Institute of Automation, Chinese Academy of Sciences, integrates flexible strain sensors into its soft actuator through an embedded design. This approach can be adapted for other soft robotics systems. By using the same structural material for both sensors and actuators, the device achieves seamless integration of actuation, sensing, and control. This breakthrough enables the robotic fish to continuously monitor its swimming dynamics and environmental fluid changes in real time, automatically switching to optimal swimming modes as needed [15].

3.3. Integration at the System and Algorithm

The integration of the system and algorithm is the key to realizing intelligent rehabilitation of flexible sensing technology. Through the fusion processing of multimodal sensing data and intelligent control algorithms, soft robots are endowed with the ability of environmental understanding, decision-making and self-adaptive adjustment, and transform from passive motion assistance tools to active rehabilitation partners.

3.3.1. Multimodal Sensor Fusion

Multimodal sensor fusion overcomes the limitations of single-sensor modalities by integrating data from diverse sensors, enabling comprehensive and accurate environmental perception. In medical rehabilitation applications, this integration proves crucial for understanding patients' complex intentions and physiological states. Inspired by the human brain's high-level perceptual model, a research team from Beijing Jiaotong University has developed a perception-movement framework based on expectation-actual matching. This framework simultaneously processes information from external interactions and internal drivers. Through multi-stage flexible sensors that integrate performance across driving, stimulation, and other scenarios, it achieves precise differentiation between external stimuli and internal deformations, with an average error rate of merely 1.4% [16].

The research team at Shanghai Tech University has developed a system that integrates temperature, pressure, thermal conductivity, and electrical conductivity sensing, enabling robots to identify object properties through tactile interaction. Studies demonstrate that combining these sensing modalities boosts material recognition accuracy from 63.99% (when using thermal conductivity alone) to 98.03%, highlighting the significant advantages of multimodal fusion [13].

3.3.2. Signal Processing and Interpretation

The signals from flexible sensors are typically nonlinear and high-dimensional, requiring advanced signal processing algorithms to extract useful information. Machine learning algorithms demonstrate strong advantages in this field, as they can adapt to the signal characteristics of different users and achieve accurate intention recognition.

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To address the significant individual differences in surface electromyography (EMG) signals, a research team from Shanghai Tech University has developed an adaptive machine learning approach that integrates a linear mapping network with a temporal onset model. This innovative method requires only three repeated gesture executions from new users to fine-tune model parameters through transfer learning, achieving personalized adaptation. The system demonstrates 98.33% classification accuracy with a latency of 0.1 seconds, paving the way for real-time interactive applications [13].

3.3.3. Closed-loop Control

Closed-loop control enables soft robots to dynamically adjust assistance strategies based on patient status and environmental changes through a real-time perception-decision-action cycle, achieving personalized adaptive rehabilitation therapy. This intelligent control strategy significantly enhances the precision and safety of rehabilitation training. The Respiratory Assistance Soft Robot System developed by the Chinese Academy of Sciences features a dual-layer intelligent control architecture. The outer layer employs flexible force sensors to monitor real-time human-machine interaction forces, dynamically adjusting the assistance intensity. The inner layer utilizes a pneumatic coordination algorithm to ensure precise synchronization between the actuator's output pressure and the breathing rhythm [18]. Clinical studies have demonstrated that the closed-loop control system enhances peak exhalation flow rate by 20.12% and tidal volume by 19.69% in patients with respiratory rates ranging from 12 to 40 breaths per minute [18]. The perception-movement framework developed by Beijing Jiaotong University's research team enables soft robots to detect the direction and magnitude of static and dynamic interaction forces in both static and dynamic configurations. This breakthrough allows successful terrain and force sensing and analysis in unobservable environments. The closed-loop system enables robots to detect contact and identify deformation sources within 0.4 seconds, providing critical technical support for safe human-robot interaction [16].

4. Specific Application Scenarios of Flexible Sensing Technology in Medical Rehabilitation

4.1. Wearable Rehabilitation Training Soft Robot

Wearable rehabilitation soft robotics stands as a flagship application of flexible sensing technology, delivering safe, comfortable, and personalized training solutions for neurological disorders like stroke and spinal cord injuries. These devices—typically designed as gloves, protective gear, or exoskeletons—integrate multiple flexible sensors to monitor patients' movements and physiological states in real time. Powered by soft actuators, they provide targeted assistance to facilitate neural rewiring and motor function recovery [19].

In lower limb rehabilitation, a robot suit equipped with flexible sensors can estimate gait phases in real time, as shown in Figure 1. This wearable robotic assistive device helps Parkinson's patients improve their 'frozen gait' [14].

In respiratory rehabilitation, research teams led by the Chinese Academy of Sciences have developed a wearable flexible respiratory assistive robot system. By establishing a thoracoabdominal biomechanical model and implementing a dual-layer intelligent control architecture (with an outer layer using flexible force sensors to monitor human-machine interaction forces and an inner layer controlling actuator air pressure), the system significantly enhances respiratory assistance effectiveness. This innovation achieves an average 20.12% increase in peak expiratory flow rate and a 19.69% rise in tidal volume for subjects [18].



Figure 1. Using flexible wearable robots to help Parkinson's disease patients walk without freezing gait [14]

4.2. Rehabilitation Medical Services

Harvard University developed a soft robotic glove that generates finger-like gripping motions through hydraulic actuation, providing optimal motion support and force output. Studies demonstrate that this soft robotic glove delivers satisfactory performance in both routine and precise grasping tasks [20].

Researchers have developed a bionic soft prosthetic hand for radial amputees. This pneumatic-driven neuroprosthetic features five anthropomorphic fingers and six degrees of freedom, controlled by four electromyography (EMG) sensors that detect surface signals from residual forearm muscles. The fingertip integrates five elastic capacitive sensors for pressure measurement, while tactile feedback is achieved through electrical stimulation of the residual limb's skin [21]. In telemedicine, the stiffness of soft hand sensory organs or tissues is enhanced to better assist medical staff in their work [22].

Soft hands are primarily constructed from flexible materials, fundamentally meeting the requirements for rehabilitation assistive devices. Their lightweight and simple structure significantly

enhances user convenience and comfort. Figure 2 presents typical application cases of soft hands in rehabilitation assistance. Among them, Figure 2b [23], Figure 2c [24], Figure 2d [25] and Figure 2e [26] are soft hands used to improve the quality of life of patients with disabilities such as stroke and assist them to grasp, and Figure 2a [27] is soft hands used for patient rehabilitation training, which also has the function of assistance.



Figure 2. Assistive rehabilitation soft equipment [23-27]

5. Conclusion

This paper systematically reviews the key technologies, integration strategies, and application scenarios of soft robotics based on flexible sensing in medical rehabilitation. Flexible sensing technology achieves high-pressure precision monitoring through resistive, capacitive, and piezoelectric sensing systems. Combined with innovative materials and optimized algorithms, an integrated drive-sensing-control system has been constructed. In clinical settings, wearable technology has been successfully applied in hand function rehabilitation and gait assistance, significantly enhancing the effectiveness and safety of personalized rehabilitation. In the future, with advancements in self-healing materials and digital twin technology, flexible sensing soft robots will evolve toward smarter and more personalized directions. Progress in materials science will address interface compatibility and durability issues, while AI algorithms will enable more precise intention recognition and adaptive control. The integration of IoT technology will break geographical barriers

for rehabilitation services, achieving seamless connections between hospitals, homes, and communities, thereby providing accessible, efficient, and comfortable rehabilitation treatments for millions of patients worldwide.

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