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COMMENTARY

Advancing medical devices with soft actuators

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Soft actuators are flexible devices or materials that mimic natural muscle movements by converting various forms of energy into mechanical motion, allowing them to mimic the dynamics of natural muscle movement and adapt seamlessly to complex biological environments.[1] These actuation mechanisms include pneumatic, hydraulic, light, electronic, and magnetic actuation (Figure 1A), each offering unique advantages for specific medical applications. For instance, electrochemical actuators, known for their high energy efficiency, are ideal for internal medical devices like implantable pumps and minimally invasive tools, where precise control and low power consumption are crucial. Pneumatic actuators provide excellent mechanical output, making them suitable for wearable devices such as exoskeletons that assist movement in rehabilitation by offering substantial force while maintaining flexibility. Fiber-shaped actuators have a unique morphology that allows for high integration into compact medical devices and smart textiles, beneficial for applications requiring miniaturization and adaptability. By taking advantage of the strengths of each actuation mechanism, soft actuators can be tailored to enhance performance across various medical technologies (Figure 1B).

The development and deployment of soft actuator-powered medical devices face significant challenges, including material biocompatibility, scalability, energy supply, integration, precision control, and regulatory hurdle (Figure 1C). By embracing these challenges and extending the frontiers of what is currently possible, soft actuators are set to redefine medical technology, enhancing the efficacy of treatments, ensuring the safety of surgeries, and making patient care more individualized and reactive.

CURRENT APPLICATIONS AND INNOVATIONS

Minimally invasive surgery (MIS): Soft actuators have revolutionized MIS by enabling the creation of highly adaptable and less invasive surgical tools. These devices are particularly beneficial in procedures that require navigation through narrow or complex anatomical pathways. For instance, soft robotic catheters, developed with advanced materials that can change stiffness in response to temperature or electrical stimuli, allow surgeons to perform precise operations inside vascular systems or other delicate environments. The flexibility of these catheters significantly reduces the risk and discomfort associated with traditional, rigid catheters. Furthermore, the integration of soft actuators in surgical grippers, surgical laser, and scissors that can conform to varying geometries allows surgeons to perform delicate tissue manipulations with the minimal risk of accidental damage. Moreover, advanced manufacturing techniques have enabled the development of micromachines using soft actuators for targeted cancer treatment. These microscale devices can navigate the bloodstream to deliver therapeutics directly to tumor sites, enhancing treatment efficacy while minimizing side effects.

Wearable medical devices: Soft actuators are at the forefront of developing responsive and adaptive wearable medical devices that enhance the quality of life for patients with mobility impairments. For instance, soft robotic gloves and sleeves are equipped with sensors and actuators that closely mimic the natural movements of human muscles (Figure 1B), providing assistance for stroke survivors and individuals suffering from muscle dystrophy or other neurological disorders. By continuously adapting to the user's muscle strength and movement patterns, these wearables assist in routine tasks while facilitating more intensive rehabilitation exercises. In a study, a textile-based soft exosuit was used to assist stroke survivors with walking, demonstrating a 7% reduction in metabolic cost and over 10% improvement in walking speed during clinical trials compared to traditional therapy.[2]

Responsive drug delivery systems: The integration of soft actuators into drug delivery systems marks a significant advancement in personalized medicine. These devices utilize materials that react to physiological cues — like changes in body temperature, pH,

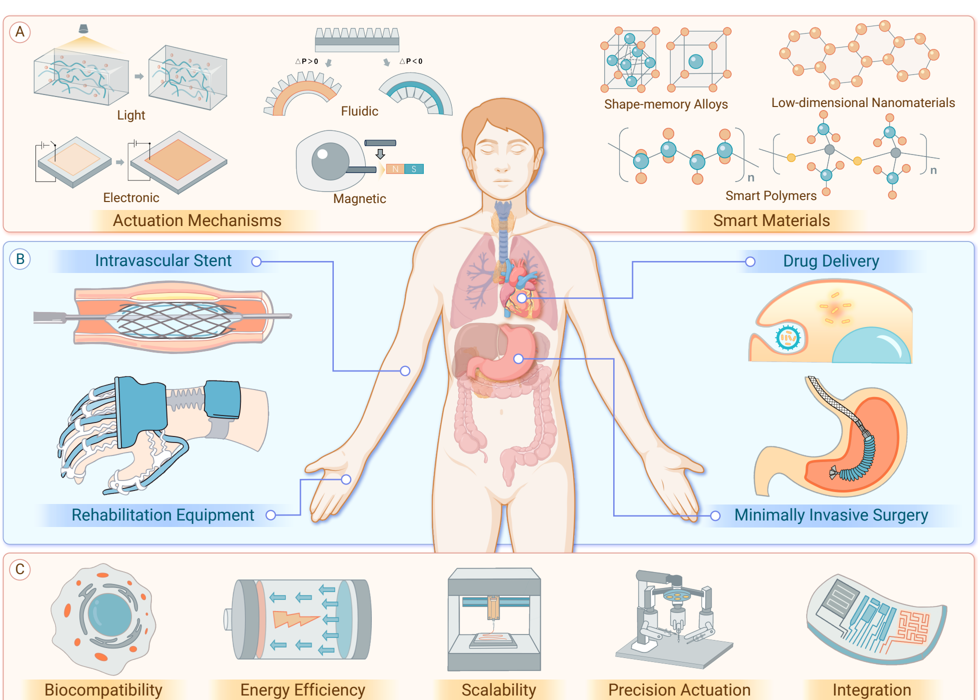

Figure 1. Materials and mechanisms of soft actuators for (A) Soft actuator materials and mechanisms for medical applications, and their (B) key application domains and (C) emerging challenges.

or even specific biomarkers—to regulate the release of medications (Figures 1A-B). Implantable drug delivery devices using pH-responsive hydrogels can swell or contract to release insulin or chemotherapy agents when triggered by changes in the patient's glucose levels or tumor microenvironment. Researchers have developed implantable insulin delivery devices using soft hydrogel actuators that maintain normal blood glucose levels in diabetic mice for up to five days without additional injections.[3] These devices utilize materials that react to physiological cues to regulate medication release, enhancing therapeutic efficacy and minimizing side effects by ensuring precise dosage and timing.

CRITICAL CHALLENGES AND FUTURE DIRECTIONS

Biocompatible soft actuator materials: One of the foremost challenges in the development of soft actuators for medical applications is ensuring that the materials used are not only flexible and responsive but also biocompatible and stable within the human body over extended periods. Many of the polymers and gels currently employed in soft actuator manufacture are susceptible to degradation and can provoke immune responses, thereby limiting their utility for long-term implantation and sustained therapeutic use. To overcome these limitations, research should pay more attention on the development of new biomaterials that inherently combine the desirable properties of existing polymers —such as flexibility and ease of processing—with the durability and inertness of inorganic materials, creating hybrid composites ideally suited for medical use. Additionally, the application of surface modification techniques such as plasma treatment plays a crucial role in enhancing biocompatibility and reducing the potential for adverse immune reactions.

Durability and reliability: Durability and reliability are critical for the successful integration of soft actuators into medical devices. Challenges such as material fatigue, wear and tear, and degradation under physiological conditions can impact the longevity of soft actuators. Research into more robust materials, protective encapsulation techniques, and self-healing polymers can enhance the durability of these devices. Accelerated life testing and real-world simulations are also essential to evaluate and improve the reliability of soft actuators in medical environments.

Scalability and manufacturing of soft actuators: The development of soft actuators relies heavily on advanced fabrication techniques that enable the incorporation of various conductive or magnetic particles into flexible matrices. Methods such as additive manufacturing (3D printing), soft lithography, and molding have been instrumental in creating complex geometries and functional composites. For instance, embedding conductive fillers like carbon nanotubes, graphene, or magnetic particles into elastomeric materials enhances their electrical and magnetic responsiveness, broadening the range of actuation mechanisms available for medical applications.[4] However, scaling the production of soft actuators to meet industrial and clinical demands presents significant challenges due to the intricate designs multi-material compositions. To overcome these obstacles, it is essential to standardize manufacturing protocols and adopt advanced fabrication techniques. Implementing automated assembly lines specifically designed for handling soft materials can reduce human error.

Additionally, as healthcare increasingly focuses on sustainability, incorporating recyclable or biodegradable materials into soft actuators is becoming essential. This approach reduces medical waste and the environmental impact of disposable medical devices.

Energy supply for soft actuators: The pursuit of energy-efficient soft actuators with embodied energy supply is critical to their practical application and sustainability in medical contexts. Traditionally, these actuators have relied on bulky battery systems that often necessitate frequent recharging or replacement, significantly limiting their functionality in long-term and remote healthcare applications. To address these limitations, innovative energy harvesting and transmission technologies are being explored to enhance the autonomy and integration of soft actuators in wearable and implantable medical devices. Power generation technologies based on piezoelectric and thermoelectric materials are promising approaches for devices that utilize the mechanical energy generated by body movement and the temperature gradient between the body and the external environment to generate electricity. Continued advances in materials science aim to produce more flexible and efficient advanced materials that can be comfortably integrated into wearable or medical devices without disturbing the body's homeostasis. Additionally, wireless power transmission technologies, including near-field and inductive coupling, are being advanced to power soft actuators without the need for direct electrical connections, thereby reducing device weight and enhancing patient comfort.

Integrating advanced electronics and enhancing precision: Integrating electronic components such as sensors and controller units into soft actuators is challenging due to the disparity between the mechanical properties of traditional electronics and flexible materials. Advances in flexible electronics have been crucial, resulting in the development of stretchable, bendable circuits that seamlessly integrate without compromising the flexibility of soft actuators. Additionally, achieving high precision in the control and actuation of soft actuators is critical, particularly in medical applications such as surgical interventions and controlled drug delivery, where even minor inaccuracies can cause significant adverse effects. The development of sophisticated control systems utilizing artificial intelligence (AI) and machine learning is essential. These systems can dynamically adapt to the variable behaviors of soft materials under different conditions, significantly improving the precision and responsiveness of actuation. For example, AI algorithms can process real-time data from embedded sensors to adjust actuation parameters, tailor movements to individual patient needs and enhanc personalized medicine. Specifically, AI algorithms and high-speed telecommunication technologies are revolutionizing the way robots interpret medical images and telemedicine.[5] By processing data from modalities like MRI (Magnetic Resonance Imaging), CT (Computed Tomography) scans, and ultrasound, AI enables robots to accurately identify and segment anatomical structures and pathological sites. This capability enhances navigation safety and expands the potential for robots to operate in more complex surgical environments. Additionally, machine learning techniques empower medical robots to perform tasks with higher levels of autonomy. Through reinforcement learning and imitation learning, robots can observe surgical procedures performed by experts and learn optimal strategies for task execution.

Regulatory and ethical challenges: Introducing soft actuator-powered devices into established clinical protocols presents substantial logistical, regulatory, and ethical challenges. The novel materials and mechanisms often lack comprehensive regulatory guidelines, making approval processes complex. Ethical considerations include patient safety, data privacy, and informed consent for emerging technologies. Collaboration with regulatory bodies to establish standards and protocols is necessary. Additionally.

To facilitate advanced device integration into medical equipment, it is essential to develop and implement comprehensive educational initiatives. training modules that are specifically tailored to the nuances of soft actuator technologies, covering critical aspects such as operational techniques, maintenance procedures, and troubleshooting methods.

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DECLARATION OF INTERESTS

The authors declare no competing interests.