

Editorial

Soft robots: Skin-inspired Electronic Implant

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Abstract

Inspired by the seamless integration of muscles and skin in vertebrates, the researcher introduces a novel design strategy for soft robots that pairs electronic skin (e-skin) with artificial muscle. This modern strategy, inspired by nature and enabled by a direct, solution-based manufacturing process, allows the formation of a single, biocompatible platform capable of multifaceted sensing and on-demand actuation. These untethered, wirelessly powered robots can achieve adaptive motion and gentle, stress-free interaction with tissues. The versatility of this design is showcased through a range of prototypes, including a blood pressure-detecting robotic cuff, a bladder-monitoring and treatment gripper, a pH-sensing and drug-delivering ingestible robot, and a cardiac function-assessing and electrotherapy-delivering robotic patch. This investigation lays the foundation for a comprehensive design plan that is flexible across a wide array of sensing and responsive materials and can enable soft robotics in medicine and beyond.

Keywords: Soft Robots; electronic skin (e-skin); bio-inspired; bio-compatible Platform, biomedical Implants

The persistence necessary to adapt to changing environments has driven the evolution of living organisms, leading to the specialized integration of sensory and motor roles [1, 2]. The seamless integration of skeletal muscles and sensory skin in vertebrates is an example of biological engineering, allowing these animals to move and interact with

their environment with surprising precision and intelligence. An ironic array of receptors surrounds the soft, pliable skin, sensitive to pressure, temperature, and pain, and further, works as an active sensory web, continuously collecting and sending data to the nervous system. This unceasing stream of perceptible data guides the muscles toward optimal

movement strategies and provides a nuanced, empathetic understanding of the surrounding environment, increasing consciousness and intellectual role [3]. Motivated by the seamless motor-sensor integration in living organisms, scientists utilize intelligent robots with soft, sensor-rich skins. This bio-inspired approach enables safer interaction with complex, unpredictable environments, particularly in applications such as precision medicine, where robots must delicately interact with biological tissues [4-6]. A key challenge in robotics is achieving the natural and fluid integration of sensing, actuation, and control found in living organisms while preserving softness and biocompatibility [7, 8]. Developing bio-inspired, touch-sensitive soft robots for implantation could revolutionize medical technology, with applications in diagnosis, prosthetics, surgery, drug delivery, artificial organs, and even rehabilitation through realistic tissue simulators [9-11]. Soft robotic implants, designed to change shape, adapt their function, and seamlessly integrate with living tissues, offer a new frontier in medical treatment. These implants can match the mechanical properties of surrounding tissues, sense and respond to biological signals, and deliver targeted therapies [9, 10].

A proposed integrated bladder system exemplifies this concept. It uses interdigitated capacitive sensors for constant-volume monitoring and a shape-memory alloy actuator for robust urine expulsion, demonstrating the potential for precise, real-time bladder control [12]. Demonstrating the potential for minimally invasive monitoring, a soft gripper made from a shape-memory polymer, embedded with silver nanowires and a crack-based strain sensor, can conform to the shape of a carotid artery in a swine model, enabling continuous blood pressure

measurement [13]. Inspired by the tenacious grip of hookworm teeth, researchers have developed “thera-grippers.” These tiny devices, made of a metal-polymer hybrid, act like miniature anchors, latching onto the intestinal lining to deliver medication directly to the GI tract over an extended period [14]. The fusion of sensing and actuation in soft robotic implants goes beyond improving diagnostic and therapeutic precision. This powerful combination allows for dynamic interaction with targeted tissues, paving the way for artificial organs capable of physical transformations and essential physiological functions, such as hormone secretion and electrical signaling [11, 14]. Despite exciting progress, soft robotic implants face a critical bottleneck in materials and manufacturing. These devices must be crafted from biocompatible materials that match the mechanical properties of living tissues, designed for long-term stability and functionality within the body, and ideally, incorporate biomimetic features to enhance their performance. Overcoming these challenges will translate this promising technology to the clinic [8, 12].

Zhang et al. [15] recently published their work in *Nature Communications*, exploring the development of untethered, biomimetic soft robots designed for seamless integration with the human body. By integrating actuators, sensors, and nature-inspired stimulators, these robots can adjust their shape and purpose dynamically, reducing tissue damage during deployment, reducing interfacial stress, and improving biocompatibility. This method overlays the approach for advanced, multimodal devices with specific spatiotemporal control, opening new options for medical mediation (Fig. 1).

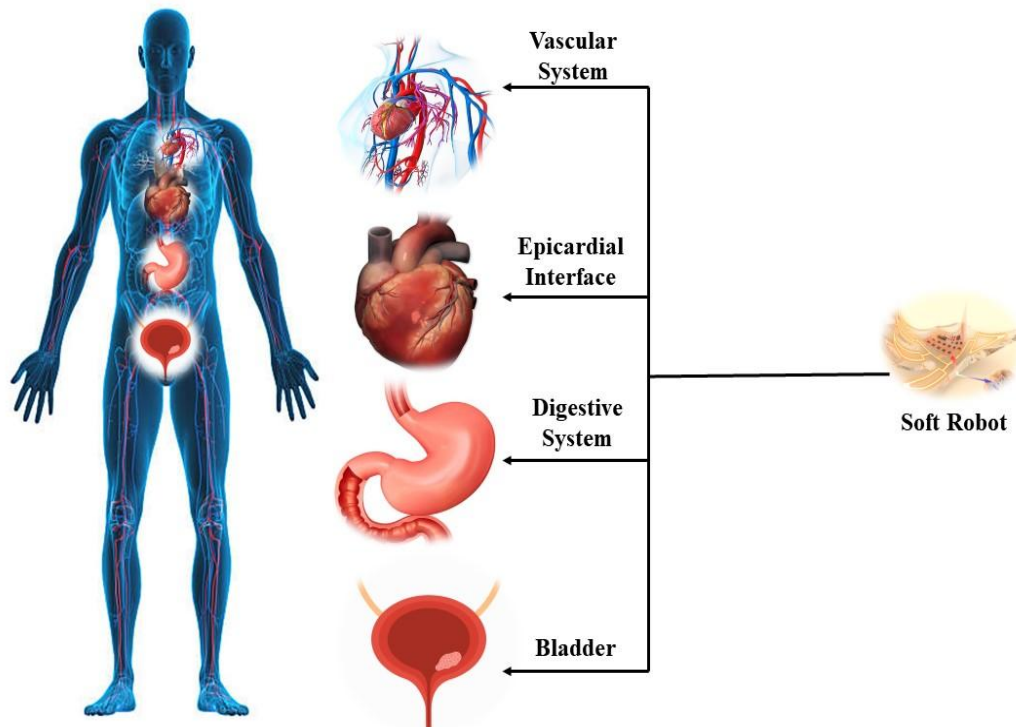


Figure 1. A schematic demonstration display of soft robots, proposed as nominally invasive smart implants, can perform diagnosis, deliver therapeutic stimulation, and control targeted drug delivery.

Zhang et al. [15] initiated an innovative method of soft robotics, drawing on the elegance of biological systems. They show unstrapped robots seamlessly incorporating actuators, sensors, and stimulators, aiding dynamic structural adjustment and reshaping interfaces. This biomimetic strategy offers numerous advantages: minimizing tissue damage throughout in vivo deployment, improving mechanical compatibility at the interface between the robot and living tissue, enhancing biocompatibility, and enabling precise, multimodal functionality. These notable robots feature a multi-layered design: an

outer "e-skin" made from multimodal nanocomposites, which mimic the extraordinary sensing abilities of biological skin, and a fundamental artificial muscle layer composed of thermally responsive PNIPAM hydrogel, allowing for adaptive movement.

Zhang et al. [15]., exploit a versatile, in-situ solution-based fabrication approach to form their flexible, multimodal e-skin. This method enables them to seamlessly incorporate functional materials, such as AgNWs, RGO, and PEDOT: PSS, into a polymeric

matrix (e.g., PDMS and PI). This facilitates the development of diverse sensors, including pressure, temperature, and strain sensors, with remarkable spatiotemporal resolution. Encouraged by nature, these soft robots demonstrate an incredible range of motion, including bending, twisting, and development. They can also produce distinct structural distortions, mimicking natural shapes such as starfish, fishbones, and chiral seedpods. Exact, autonomous control of identifiable regions within the soft body is achieved through on-demand actuation initiated via electrothermal stimulation from electrical heaters implanted within the e-skin. Also, incorporating wireless modules enables control and communication with robots, even when they are inserted into the body.

Zhang et al. [15] showcase the significant adaptability of their soft robot design by forming tailored devices for a range of medical purposes. These contain a soft robotic gripper proficient in wrapping around the bladder to both monitor volume and deliver electrical stimulation for curing overactive bladder; a robotic cuff premeditated to twist around a blood vessel for blood pressure measurement; and an ingestible robotic cuff premeditated to twisted around a blood vessel for blood pressure measurement, and even an ingestible robot able to exist in the stomach for constant pH monitoring and targeted drug delivery. The researcher demonstrated the capabilities of their equipment via in vivo studies using a mouse model. A soft robotic “thera-gripper” smoothly enveloped a beating heart, demonstrating its ability to assess spatiotemporal electrophysiological activity, quantify cardiac contractility, and deliver electrical stimulation for functional regulation. These convincing explanations emphasize the soft robots'

ability to reform biomedical implants, offering a compelling combination of structural intelligence and multifunctionality. Future research will enhance the synergistic relations between these implantable robots and living tissues, leading to long-term biocompatibility and stability within dynamic physiological environments. Such innovations hold great promise for transforming the treatment of chronic diseases.

The investigation by Zhang et al. [15], symbolizes substantial progress in the field of bio-inspired soft robots for medical applications. The novel plan and the incorporation of multifunctional sensors and actuators within a biocompatible platform offer promising opportunities for diverse medical applications. Future research that addresses existing limitations and improves the functionality of these devices will be vital to realizing their full potential and advancing medical technology. Although the study demonstrates the viability of bio-inspired soft robots, numerous areas warrant further research. Improving the durability and longevity of exhaust materials, enhancing devices' biocompatibility, and advancing scalable fabrication processes are critical to translating these advances into clinical practice. Also, investigating the incorporation of more sophisticated sensors and increasing the robots' wireless communication capabilities could further enhance their functionality and consistency.

Declaration of Competing Interest

The author declares no competing financial interests.

Authorship contribution statement

Humayun Yousaf: Investigation, writing original draft, Writing e review & editing. Noor Zada Khan:

Supervision, Conceptualization, Writing, review & editing.

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