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Research Highlight

Building soft and conformal bioelectronic interfaces *via* a water-responsive supercontractile polymer film

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In the thriving era of the Internet of Things (IoT), there is an escalating inclination towards establishing comprehensive connectivity, not only for linking external entities but also for connecting human body to external environment [1]. While the internet and portable electronics have largely achieved the former goal, the challenge of linking the human body and biological systems to the external environment persists. Fortunately, the advent of flexible and wearable electronics presents a viable solution towards accomplishing this ambiton. The incorporation of flexible sensors onto human body enables the capture of diverse body-related information, spanning biophysical, biochemical, and physiological signals [2]. This integration serves to establish a direct connection between the human body and external world, enabling versatile applications such as health monitoring, disease diagnosis and therapy, and human–machine interactions.

Over the past two decades, the trajectory of flexible electronics research has notably shifted from near-body wearable devices to on-skin and in-body-centric ones, delineated by the nomenclature ‘‘epidermal” and ‘‘implantable” bioelectronics [3,4]. However, the integration of bioelectronics with the human skin or biological tissues encounters significant challenges at the interfaces between the skin/tissue and electronics for achieving seamless and intimate integration [5]. Notably, human skin and biological tissues are mostly soft, wet, and curvilinear, while materials of conventional electronics are rigid, dry, and planar. These disparities, known as mechanical and geometric mismatches, represent a fundamental hurdle in the development of conformal bioelectronics [6]. Addressing these limitations has seen recent advancement in developing flexible, soft, and conformal materials, such as thin films, porous fiber meshes, and soft hydrogels [7–11]. Nonetheless, the majority of these materials, with pre-designed shapes and sizes, struggle to conform precisely to the diverse and dynamic shapes of biological tissues. This inadequacy stems from tissues' arbitrary shape, size and their evolving nature, responding to environmental stimuli and temporal changes. Consequently, there is an imperative to explore materials that are not solely soft and stretchable but also possess shape adaptive or morphing qualities [12,13], allowing them to flexibly conform to tissues and dynamically change alongside tissue deformations.

Stimuli-responsive polymers hold promise for making bioelectrodes capable of changing their shapes. However, the usual stimuli conditions for these polymers—such as ultraviolet light, high temperatures, and acidic/alkaline solutions—are incompatible with the physiological environments. For instance, heat-shrink films made of polyvinyl chloride can contract largely and rapidly upon heating, yet necessitate high temperatures (∼90 °C), and often resulting in rigid solid films. Till now, there is a scarcity of stimuli-responsive materials that can be triggered by the gentle physiological conditions such as water, body temperature, and neutral pH. Recently, Yi et al. [14] at Nanyang Technological University reported an innovative water-responsive shape-adaptive polymer termed WRAP, which exhibits the ability to contract upon exposure to water at ambient conditions. Upon wetting, the film contracts by more than 50% of its original length within seconds (about 30% per second) and transforms into a thin, soft, and stretchable hydrogel film. Such a gentle triggering condition is compatible with biological tissues, and allows the construction of soft, stretchable and conformal tissue–electronic interfaces.

The creation of WRAP films drew inspiration from the impressive supercontraction observed in spider silk [15]. Spider silks have a hierarchical structure consisting of oriented polymer chains embedded in amorphous domains, held together by hydrogen bonds and β-sheet crystallites. The highly oriented polymer chains are fixed in the amorphous domains by hydrogen bonds. Upon wetting, these hydrogen bonds break, initiating a molecular chain recoil that leads to supercontraction [16]. Herein, Yi et al. [14] mimicked this hierarchical structure by blending a water-soluble semicrystalline polymer (poly(ethylene oxide), PEO) with an inclusion complex (IC). In the blend, the molecular chains of semicrystalline PEO are arranged in an oriented manner mimicking the oriented polymer chains in spider silk, while the IC serves a function akin to a crosslinker, resembling the role played by β-sheet crystallites in spider silk. In detail, they first prepared the IC gel by mixing poly(ethylene glycol) (PEG) and α-cyclodextrin (α-CD) through host–guest supramolecular interactions. Then, a PEO solution was mixed with the pre-made IC gel and dried to produce a free-standing IC/PEO thin film (Fig. 1a). Subsequently, a repeated

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cold-drawing process was applied to stretch the IC/PEO films, by which a series of WRAP films were obtained with the ultimate elongation ratio ranging from 218% to 700% (Fig. 1b).

The dry, flexible, and free-standing WRAP films remain stable under ambient conditions with humidity lower than 80%, while shrinking immediately upon contacting water. Fig. 1c illustrates the water-induced rapid contraction, where can see a piece of WRAP film contracted about 60% within 2 s. Notably, the contraction ratio can be readily adjusted from 35% to 65% by controlling the elongation ratio in the cold-drawing process. After contraction, the resulting hydrogel thin films are soft and stretchable, featuring very low Young's modulus (ranging from 225 to 20 kPa), making them a perfect match for tissues such as peripheral nerves. Moreover, the confining pressures exerted on tissues, such as peripheral nerves, after wrapping are well below the threshold of nerve damage, underscoring its soft and safe characteristics. The ability to transition from a dry film to a soft and stretchable hydrogel not only facilitates the on-demand construction of conformal bioelectronic interfaces, but is also beneficial in electronic fabrication, given that dry and stiff films are more easily handled.

The authors meticulously investigated the supercontraction mechanism of the WRAP films, emphasizing the pivotal role played by the oriented PEO molecular chains. As depicted in Fig. 1d, the isotropic semi-crystalline PEO chains are stretched to be oriented by cold-drawing, validated by polarized FTIR spectroscopy, differential scanning calorimetry (DSC), and 2D Wide-angle X-ray scattering. After cold-drawing process, the oriented PEO molecular chains are provisionally fixed by recrystallized PEO domains. Upon exposure to water, water breaks and dissolves these PEO domains, inducing supercontraction. In addition, the IC component plays an essential role in stabilizing the resulting hydrogels, preventing rapid dissolution.

As a proof of concept, they exemplified the patterning of conductive electrodes (e.g., Au) on the WRAP films, showcasing the fabrication of electrode arrays intended for peripheral nerve stimulation and electrophysiological signals recording. The Au-coated WRAP electrode can adaptively wrap onto the nerve and achieve conformal wrapping (Fig. 1e, f). Owing to the shape-adaptive capability, WRAP electrodes with the same size can conformally wrap around nerves of varying sizes, including rat sciatic nerve (~1.3 mm), common peroneal nerve (~0.5 mm), tibial nerve

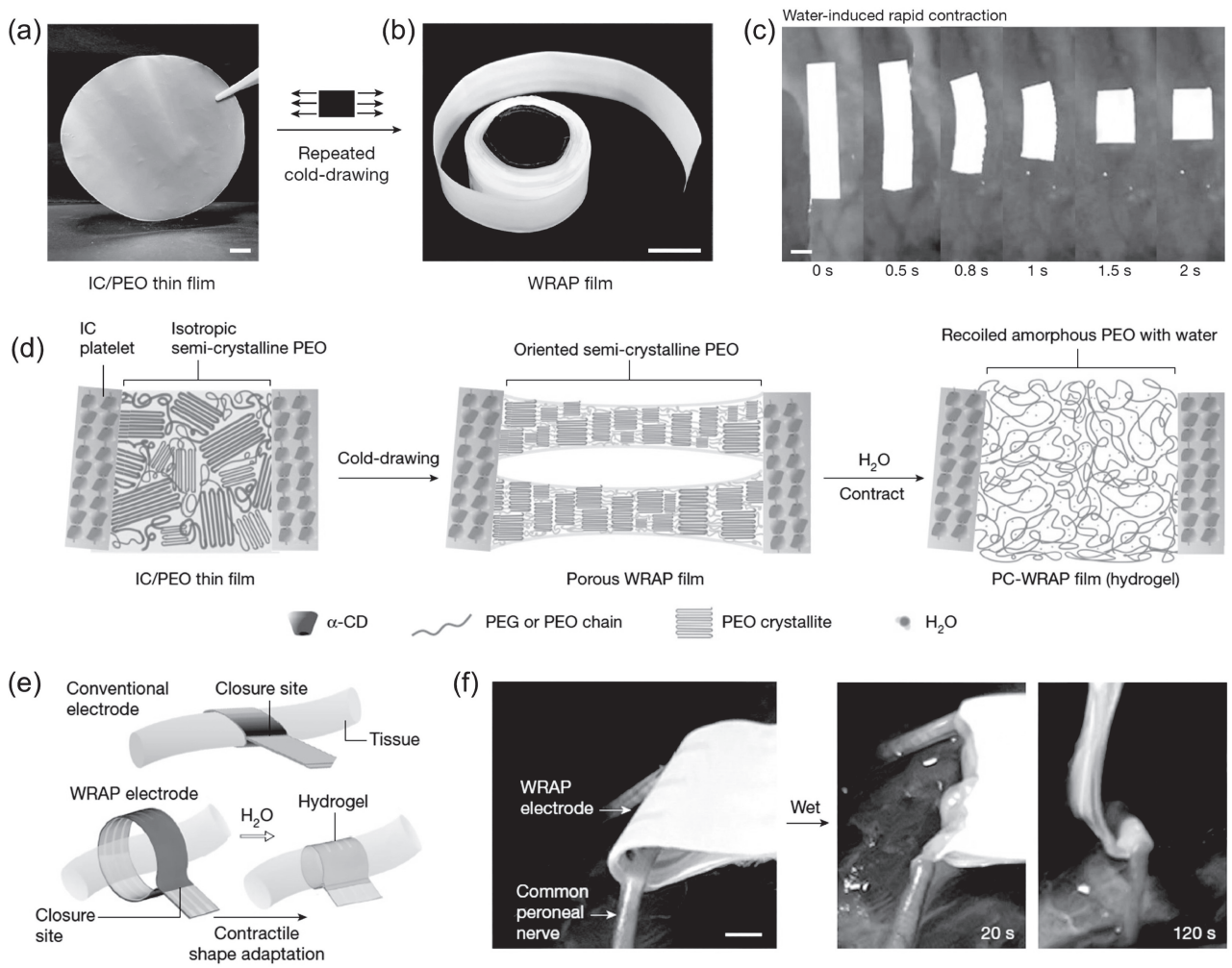

Fig. 1. (Color online) Photographs of prepared IC/PEO thin film (a) and the WRAP film (b) after repeated cold-drawing. (c) Rapid water-induced supercontraction of WRAP film. WRAP film contracted about 60% within 2 s when wetted. (d) Schematic showing microstructure formation on mechanical elongation and supercontraction mechanism of a WRAP film. (e) Schematic showing that the implantation procedures of the WRAP electrodes are simpler and safer compared with those of the conventional electrodes. (f) WRAP electrode loosely looped around the common peroneal nerve contracted and conformally wrapped within 2 min when wetted. Scale bars, 1 cm (a), 5 mm (b); 3 mm (c); 1 mm (f). Reproduced with permission from Ref. [14], Copyright © 2023, Springer Nature.

(∼0.7 mm), tibialis anterior muscle (∼13.0 mm), and soleus muscle (∼6.0 mm). The WRAP electrodes showed lower electrical resistance, lower impedance, and higher charge-injection capacity than conventional Au-elastomer electrodes. As a result, the WRAP electrodes successfully achieved high-quality recordings in a range of signals, encompassing large-amplitude compound action potential, small-amplitude nerve electroneurogram (ENG), peripheral nerve electromyography (EMG), and epicardial electrogram (EGM).

In summary, Yi et al. [14] developed a water-responsive supercontractile polymer film (WRAP) via mimicking the hierarchical structure of spider silk. This WRAP film exhibits remarkable contractable behavior when exposed to water under ambient conditions, transitioning from a dry film to a soft and stretchable hydrogel. The material holds significant promise for constructing soft and conformal interfaces between electronic and biological tissues. Generally, this on-demand formation of soft hydrogel electrodes through wetting a pre-fabricated dry film inspires us to innovate a range of ready-to-use bioelectrodes and devices for conformal bioelectronic interfaces. Alongside the development of inherently contractile or extensible materials for crafting conformal bioelectrodes, other manufacturing methods like 3D printing could be utilized for constructing these bioelectrodes, thereby enabling the development of programmable 4D bioelectrodes [17]. Despite its advancements, there is room for further enhancement in the performance of WRAP films. For instance, the as-developed WRAP film utilizes a water-soluble polymer with a low crosslinking degree, potentially leading to long-term stability issues in physiological environments. Additionally, the current WRAP films may lack strong adhesive properties, particularly in aqueous conditions within the body, necessitating improvement in adhesive characteristics. Furthermore, while the WRAP electrode addresses the mechanical mismatch at tissue–electrode interfaces, its use of a rigid metal wire for external connection may introduce new mechanical mismatch issues. Last but not least, biocompatibility stands as another crucial consideration, imposing constraints on both material selection and fabrication techniques for developing bioelectronics intended for on-skin and implantable applications. Therefore, addressing the mechanical mismatch at multiple levels, including biological interfaces, materials, and devices, remains an ongoing challenge in the development of practical soft and conformal bioelectronics. The continuous advancements in materials synthesis, device manufacturing, system integration, and biomedical protocols will lay the foundation for the development of future bioelectronics, enabling seamless connections between the human body and external environments.

Conflict of interest

The authors declare that they have no conflict of interest.

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References

[1] Gong S, Lu Y, Yin J, et al. Materials-driven soft wearable bioelectronics for connected healthcare. Chem Rev 2024;124:455–553.
[2] Kim J, Campbell AS, de Ávila B-E-F, et al. Wearable biosensors for healthcare monitoring. Nat Biotechnol 2019;37:389–406.
[3] Kim D-H, Lu N, Ma R, et al. Epidermal electronics. Science 2011;333:838–43.
[4] Zhou T, Yuk H, Hu F, et al. 3d printable high-performance conducting polymer hydrogel for all-hydrogel bioelectronic interfaces. Nat Mater 2023;22:895–902.
[5] Li N, Li Y, Cheng Z, et al. Bioadhesive polymer semiconductors and transistors for intimate biointerfaces. Science 2023;381:686–93.
[6] Li Y, Li N, Liu W, et al. Achieving tissue-level softness on stretchable electronics through a generalizable soft interlayer design. Nat Commun 2023;14:4488.
[7] Jiang Z, Chen N, Yi Z, et al. A 1.3-micrometre-thick elastic conductor for seamless on-skin and implantable sensors. Nat Electron 2022;5:784–93.
[8] Jiang Y, Ji S, Sun J, et al. A universal interface for plug-and-play assembly of stretchable devices. Nature 2023;614:456–62.
[9] Lee S, Franklin S, Hassani FA, et al. Nanomesh pressure sensor for monitoring finger manipulation without sensory interference. Science 2020;370:966–70.
[10] Choi H, Kim Y, Kim S, et al. Adhesive bioelectronics for sutureless epicardial interfacing. Nat Electron 2023;6:779–89.
[11] Zhang Z, Yang J, Wang H, et al. A 10-micrometer-thick nanomesh-reinforced gas-permeable hydrogel skin sensor for long-term electrophysiological monitoring. Sci Adv 2024;10:eadj5389.
[12] Liu Y, Li J, Song S, et al. Morphing electronics enable neuromodulation in growing tissue. Nat Biotechnol 2020;38:1031–6.
[13] Tian Q, Zhao H, Wang X, et al. Hairy-skin-adaptive viscoelastic dry electrodes for long-term electrophysiological monitoring. Adv Mater 2023;35:2211236.
[14] Yi J, Zou G, Huang J, et al. Water-responsive supercontractile polymer films for bioelectronic interfaces. Nature 2023;624:295–302.
[15] Liu Y, Shao Z, Vollrath F. Relationships between supercontraction and mechanical properties of spider silk. Nat Mater 2005;4:901–5.
[16] Cohen N, Levin M, Eisenbach CD. On the origin of supercontraction in spider silk. Biomacromolecules 2021;22:993–1000.
[17] Ni C, Chen D, Yin Y, et al. Shape memory polymer with programmable recovery onset. Nature 2023;622:748–53.

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