A hydrogel-based iontronic-reservoir-enabled neuromorphic prosthetic system

We developed a hydrogel-based iontronic reservoir system as a neuromorphic neuroprosthesis. It achieved more than 90% accuracy on multiple recognition tasks, muscle fatigue sensing via pH-responsive dynamics of its self-healing hydrogels, and rapid and robust functional recovery (0.02 s). The system supported adaptive closed-loop neural stimulation in vivo based on voice commands and muscle states.

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The question

Neuromorphic engineering has been reshaping the interaction between artificial devices and biological systems[1,2]. For example, an artificial sensorimotor loop (a system that integrates sensory feedback and actuation) designed with neuromorphic pulse-train signalling enabled direct communication between the biomimetic system and the biological nerve[1]. Thus, the translation of neuromorphic devices into neuroprostheses (neuromorphic prostheses) is emerging as an innovative technological route for realizing seamless integration of artificial devices with the human body.

Although neuromorphic devices strive to emulate neurons in all respects, neuromorphic prostheses still lack the ability to restore functions to injured nerves ranging from basic neural signalling to high-level cognitive functions. Previous self-healing neuromorphic devices (such as a memtransistor using self-healing ionic gels as gate dielectric[3]) can restore synapse-like behaviours they emulate, but this fails to mimic the cognitive capabilities being targeted (such as classifying and inferring). They also lack physical and functional robustness against mechanical disruptions, often requiring retraining post-damage, which limits clinical translation. Can a neuromorphic platform that combines neuromorphic computing power, physical and functional robustness, and biocompatibility be developed? Could such a platform contribute to neural rehabilitation and related closed-loop therapeutic applications in a neuroprosthesis?

The solution

We focused on designing and validating a hydrogel-based iontronic reservoir (HIRE) system. The iontronic dynamics of its electrical double layer, characterized by nonlinearity and fading memory, match the core requirements of reservoir computing (RC)[4] well. In addition, these dynamics of electrical double layers are confined to nanometre-scale Stern and diffuse layers at electrolyte–electrode interfaces[5], a property that theoretically minimizes susceptibility to physical deformation in our reservoir. Notably, certain materials (such as the self-healing hydrogels (SHHs) we employed) can retain such iontronic dynamics even after undergoing mechanical fracture. The core device of HIRE – the SHH device – adopted a three-terminal planar memcapacitor architecture, with the SHH as the dielectric layer and laser-induced graphene as the electrodes (Fig. 1a). Interestingly, its iontronic dynamics can be modulated by pH, which made the SHH device suitable for implementing RC and pH sensing simultaneously.

The HIRE-based RC system we developed had physical and functional robustness and enabled adaptive closed-loop neural stimulation needed for control of a neuromorphic prosthesis, with our experiments yielding several key findings. The HIRE-based system demonstrated a highly efficient time-series processing capability, achieving more than 90% recognition accuracy across diverse tasks (including with spoken digits, electrocardiogram signals and human actions). Upon reattachment of fractured surfaces, it exhibited rapid recovery of time-series processing functionality (within approximately 0.02 s), which is orders of magnitude faster than functional recovery in previous self-healing electronics. Crucially, the implanted SHH device's pH-responsive dynamics enabled the HIRE-based system to support muscle fatigue sensing via monitoring the local pH of the target muscle, thereby enabling adaptive intensity modulation of stimulation applied to the motor nerve of a rat (Fig. 1b). In short, this design not only recognized human commands and converted them into motor responses but also prevented acidosis that arises following prolonged muscle activity, and both functions of the HIRE system can be rapidly restored.

The implications

Our work presents a promising approach for developing a neuromorphic neuroprosthesis with both physical and functional robustness against unpredictable mechanical disruptions. Our findings also reveal the HIRE-based RC system's potential for adaptive sensorimotor function restoration or enhancing intelligence of biohybrid systems, with implications for enhancing neuromorphic devices as viable artificial interfaces with the brain.

The current validation primarily used a rodent model and predefined recognition tasks. The system's long-term stability, biocompatibility for chronic implantation and capacity to interface with neural circuits in the central rather than peripheral nervous system require further investigation. Our findings do not yet confirm equivalent efficacy in more advanced animal models or for restoring higher-order cognitive functions beyond sensorimotor loops.

Next, we will focus on the miniaturization of the HIRE-based RC system to enable standalone implantable applications and on the exploration of the system's capacity for learning more advanced tasks. We also plan to develop a multi-channel HIRE array for complex neural restoration and more sophisticated control over neuroprostheses.

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EXPERT OPINION

"The authors introduce a robust iontronic reservoir that enables reliable neuromorphic signal preprocessing even after physical damage. By confining adaptive dynamics to nanoscale interfacial processes rather than bulk device operation, this work establishes a materials-driven strategy for fault tolerant neuromorphic prostheses. This approach addresses a key bottleneck in the field as bio-integrated electronics increasingly move from demonstration of device-level functionality toward real-world and implantable applications." **Tae-Woo Lee, Seoul National University, Seoul, Republic of Korea.**

FIGURE

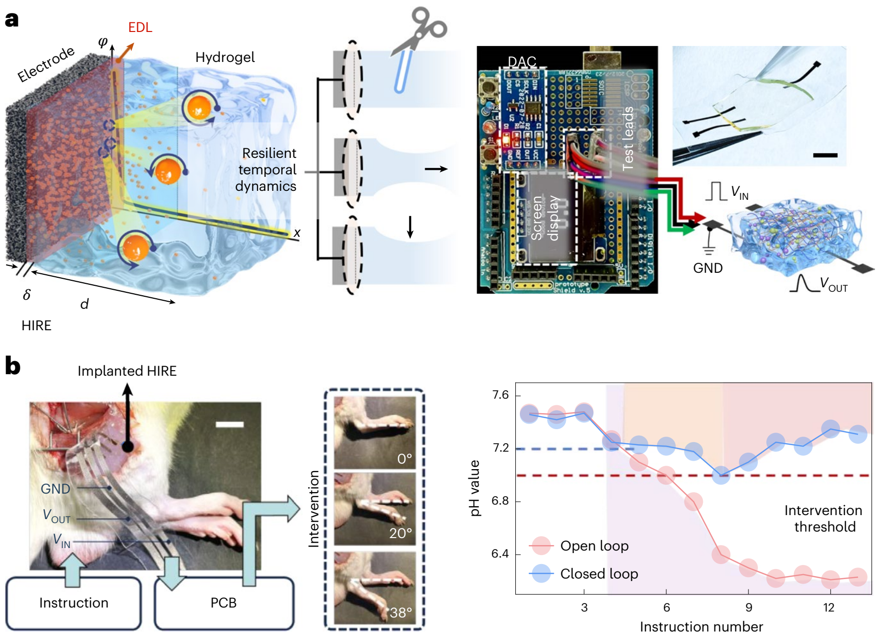

Fig. 1 | HIRE system. a, The SHH device consists of an electrical double layer (EDL) formed at the hydrogel–electrode interface as a reservoir exhibiting resilient iontronic (temporal) dynamics to mechanical deformations including cutting, stretching and compression (left). The HIRE-based system consists of the SHH device, a printed circuit board (PCB) that acquires reservoir states from the SHH device via three electrodes (V_{IN}, V_{OUT}, GND), and a digital-to-analogue converter (DAC) module that generates outputs (right). **b**, With an SHH device implanted near a rat leg muscle, the HIRE system receives and recognizes voice instructions, delivering electrical stimulation to the sciatic nerve (left). The stimulation intensity (reflected in leg movement angles) is controlled via open-loop (using only instruction recognition) or closed-loop (employing instruction recognition dynamically adjusted for muscle state using local pH levels; moderate (blue) and fatigued (red)) control, with differential effects on pH over time (minimal muscle movement at intervention threshold, pH = 7) (right). Scale bars, 1 cm. © 2026, Pei, M. et al.

BEHIND THE PAPER

Our original intention was to develop an implantable neuromorphic prosthesis that can 'translate' human voice commands and interact adaptively with animals. However, after a few attempts, we found that although conventional physical reservoirs (such as memristors or memcapacitors) enable the implementation of RC for speech command recognition, these devices were either non-biocompatible or fragile. We thus switched to using mechanically robust, biocompatible and SHHs after consulting with our collaborators in soft materials. We later realized that, unlike bulk dynamics-based conventional reservoirs, hydrogels could also be recognized as a novel platform — iontronic reservoirs — relying on interfacial dynamics. Iontronic reservoirs proved to be resilient to mechanical disruption (mostly from bulk regions) and quickly recoverable post-connection rebuilding. Hence, we finalized this hydrogel-based design, hoping that it can not only mimic neuronal rehabilitation as a neuroprosthesis but also initiate the development of neuromorphic-powered devices into interfaces with the brain. **C.W. & X.C.**

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FROM THE EDITOR

"Neuromorphic prostheses take advantage of neuromorphic functions; a major challenge that needs to be addressed is their robustness against dynamic, complex physiological environments. The authors report a neuromorphic prosthesis made of a self-healing hydrogel and electrodes, realizing an interface that can act as a physical reservoir. It restores neuromorphic capability within 0.02 s after fractured points are reattached." **Editorial Team, *Nature Materials*.**