FLEXIBLE ELECTRONICS

Soft circuits that self-heal under water

Electronic skins that are able to restore their function when damaged in aquatic conditions could be used to create durable underwater soft robots.

Carmel Majidi

Our skin has the ability to heal without external intervention or treatment. Moreover, our wounds do not usually impair our ability to carry on with a task and tend to be no more than a fleeting annoyance. This combination of self-healing and robustness is easy to take for granted, but is essential for our ability to engage in daily tasks and to physically interact with the environment. Electronic skins, which could be used to create a new generation of soft machines and robots, have similar requirements.

Unlike conventional technologies, soft machines and robots are primarily composed of gels, rubbers, fluids and other soft materials that match the mechanical properties of natural biological tissue and organs[1]. This allows the robots to be mechanically compliant and more capable of emulating the extraordinary mechanical versatility of natural organisms. It can also lead to improved safety by enabling physical interactions with the human body without causing painful contact forces that lead to discomfort or injury. However, replacing the hard plastics and metals used in traditional engineering with soft materials does introduce new challenges in terms of wear and tear. This is especially true for the conductive materials and circuitry used to form a soft robot's artificial skin. Delicate electronics are typically housed in a hard case that protects them from damaging cuts and punctures, but in soft machines and robots there is no hard case. Instead, the electronics should, as well as being soft and deformable, mimic the ability of natural skin to withstand mechanical damage from tearing, scratches and punctures. Writing in *Nature Electronics*, Chao Wang, Benjamin Tee and colleagues now report an electronic skin that is simultaneously soft, ionically conductive, optically transparent, self-healing and can function entirely underwater[2].

The researchers — who are based at Tsinghua University, the University of California Riverside, the National University of Singapore, and the Agency for Science Technology and Research in Singapore — fabricated the electronic skin by combining a fluorocarbon elastomer with a fluorine-rich ionic liquid. Previous techniques to create self-healing materials have relied on reversible ion–dipole interactions in order to repair bonds that are broken by mechanical damage[3]. The approach of Tee and colleagues builds on this technique by replacing the hydrophilic liquid in these gels with a hydrophobic solution (Fig. 1a) that enables the material to function in a water bath or other aqueous environments.

The researchers use this method to create touch, pressure and strain sensors, and also show that the material can be printed into soft ionic circuit boards. The fact that the material offers a combination of optical transparency and underwater functionality also suggests that it could be used as an electronic skin for aquatic soft robots that can swim in close proximity to sea creatures without disrupting their natural activity. Moreover, this work adds to a growing body of research in which gels have been used as a functional material for underwater soft robots[4–6] (Fig. 1b).

The work of Tee and colleagues is an important step in the development of self-healing electronic skins for soft robots, but there are plenty of opportunities for continued research in the area. To start, although the ionically conductive gel created by the researchers is capable of some sensing and circuit wiring functionalities, it is not well-suited to digital circuit applications

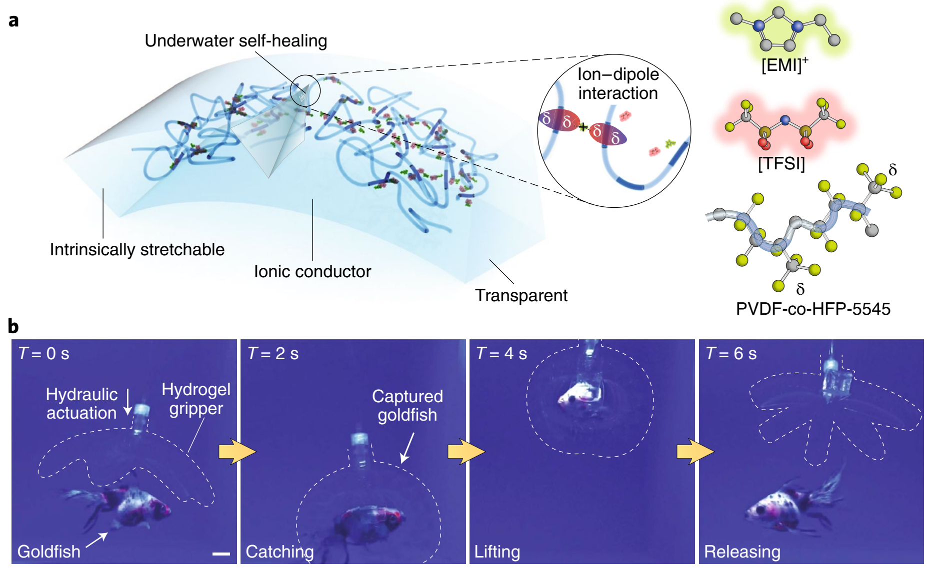

Fig. 1 | Emerging gel technologies for underwater soft robotics. a, Schematic of the optically transparent, self-healing, conductive gel developed by Tee and colleagues[2]. The gel is made by combining a fluorocarbon-based polymer (PVDF-co-HFP-5545) with a fluorine-rich ionic liquid ($[EMI]^+[TFSI]^-$). The polymer network interacts with the ionic liquid via highly reversible ion–dipole interactions, allowing it to self-heal. **b**, Transparent hydrogel gripper previously created by Xuanhe Zhao and colleagues[4]. Here the hydrogel actuator was used to catch, lift and release a goldfish. The dotted lines indicate the boundary of the transparent hydrogel structures. Scale bar, 1 cm. Credit: panel **a** reproduced from ref. [2] and panel **b** reproduced from ref. [4], Springer Nature Ltd.

that require high electronic conductivity. A promising alternative, which would have the right electrical properties for digital circuitry, is elastomers embedded with a connected network of liquid metal droplets that can self-reconfigure in response to mechanical damage[7]. However, these materials do not have the optical transparency and mechanically self-healing properties of the conductive gel constructed by Tee and colleagues[2]. Therefore, in order to build a self-healing electronic skin that is truly universal — and can thus support a wide range of circuit and sensing functions under both dry and aquatic conditions — work remains to be done.

Another important open challenge is to look beyond wiring and sensing applications and engineer self-healing circuits capable of far more complex signal processing and gated logic. Such 'artificial nervous tissue' could be integrated into the limbs of a soft robot and used to regulate motion and response to external stimuli. As with electronic skin, these soft processing circuits must also be mechanically robust and self-healing so that they can operate continuously through real-world wear-and-tear. Such advances in soft machines and electronics are necessary in order to develop robots that are intrinsically safe for physical interaction with humans, animals and delicate objects. ❐

Carmel Majidi
Soft Machines Lab, Carnegie Mellon University, Pittsburgh, PA, USA.
e-mail: cmajidi@andrew.cmu.edu

Published online: 15 February 2019
https://doi.org/10.1038/s41928-019-0208-3

References

1. Rich, S. I., Wood, R. J. & Majidi, C. *Nat. Electron.* **1**, 102–112 (2018).
2. Cao, Y. et al. *Nat. Electron.* https://doi.org/10.1038/s41928-019-0206-5 (2019).
3. Cao, Y. et al. *Adv. Mater.* **29**, 1605099 (2017).
4. Yuk, H. et al. *Nat. Commun.* **8**, 14230 (2017).
5. Katzschmann, R. K. et al. *Sci. Robot.* **3**, eaar3449 (2018).
6. Christianson, C. et al. *Sci. Robot.* **3**, eear1893 (2018).
7. Markvicka, E. J., Bartlett, M. D., Huang, X. & Majidi, C. *Nat. Mater.* **17**, 618–624 (2018).