to complete the requirements. The Caribbean Tsunami Information Center (CTIC) in Barbados, established in 2013, will further support these and other efforts to increase tsunami resilience.

Although it now takes about a minute to detect sizable earthquakes and most countries have warning points and operational procedures in place, the time it takes to detect a tsunami and communicate its impact can be reduced further. Also, the tsunami warning system is primarily triggered by earthquakes detected by seismic stations; in the event of a volcanic eruption or landslide not associated with an earthquake, it is likely that no tsunami message would be issued based on current technology. This shortcoming is being addressed but will require advances in both sensing and our understanding of non-seismically induced tsunamis. Furthermore, most coastal communities still require evacuation maps and signs, while all require the ongoing education of their residents and visitors. Significant headway has been made, but additional economic resources are still required to sustain and strengthen our warning system. By making these investments, we will not only save lives and protect livelihoods from tsunamis, but will be better prepared for earthquakes and other coastal hazards.

### References and Notes

1. NOAA National Geophysical Data Center, NOAA/WDS Global Historical Tsunami Database, www.ngdc.noaa.gov/hazard/tsu_db.shtml, accessed June 2013.
2. X. W. Proenza, G. Maul, *Sci. Tsunami Haz.* **29**, 70 (2010).
3. D. E. McNamara, C. von Hillebrandt, *Seismol. Res. Lett.* **80**, 344 (2009).
4. UNESCO, Intergovernmental Oceanographic Commission (IOC), Twenty-Third Session of the Assembly, Reports of Governing and Major Subsidiary Bodies, 109 Paris, 21 to 30 June 2005.
5. A. Hoechner, M. Ge, A. Y. Babeyko, S. V. Sobolev, *Nat. Hazards Earth Syst. Sci.* **13**, 1285 (2013).
6. J. J. Braun *et al.*, *Eos* **93**, 89 (2012).
7. IOC, Tsunami and other Coastal Hazards Warning System for the Caribbean and Adjacent Regions, CARIBE EWS Implementation Plan, IOC Technical Series No. 73 rev (2013).
8. IOC, Eighth Session of the Intergovernmental Coordination Group for the Tsunami and other Coastal Hazards Warning System for the Caribbean and Adjacent Regions (ICG/CARIBE EWS-VII), Port of Spain, Trinidad and Tobago, 30 April to 1 May 2013.

**Acknowledgments:** The author is chair of the UNESCO IOC Intergovernmental Coordination Group for Tsunamis and other Coastal Hazards for the Caribbean and Adjacent Regions and the past president of the Seismological Society of America.

10.1126/science.1238943

---

MATERIALS SCIENCE

# A Clear Advance in Soft Actuators

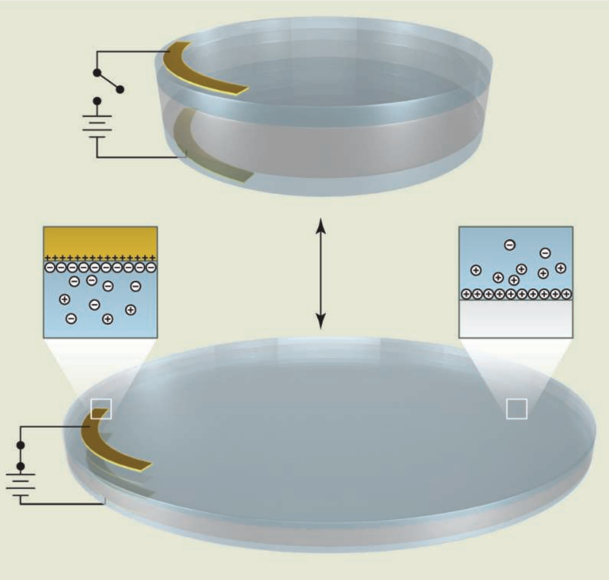
Soft, ionic hydrogels provide transparent, compliant electrodes that could be used in electrostatically controlled artificial muscles.

**John A. Rogers**

Development of actuator technologies with capabilities that can match or exceed those found in biology represents a topic of long-standing interest within the advanced robotics community. One promising and remarkably simple class of such an "artificial muscle" exploits a dielectric elastomer (an electrical insulator) sandwiched between a pair of mechanically compliant electrodes (*1*, *2*). Electrostatic force generated by an applied voltage deforms the dielectric and causes rapid, controlled displacements with large amplitudes. On page 984 of this issue, Keplinger *et al.* (*3*) describe an important advance in this dielectric elastomer actuator (DEA) technology, in which the authors replace the electrodes with soft, ionic hydrogels. The result provides a clever solution to a daunting materials challenge; it enables delivery of high voltages for fast, effective operation without any mechanical constraint on the motions of the dielectric, in a form that also provides almost perfect optical transparency.

Films of carbon powder or grease loaded with carbon black served as electrodes for the earliest DEAs (*1*, *2*). Although valuable for initial prototypes, such materials have poor reliability and are not readily compatible with established manufacturing techniques. Improved characteristics can be achieved with alternatives based on sheets of graphene (*4*), coatings of carbon nanotubes (*5*), surface-implanted layers of metallic nanoclusters (*5*), and corrugated or patterned films of metals (*5*). These options yield working DEAs, but with limited mechanical properties, sheet resistances, switching times, and capacity to integrate into advanced actuator designs. The authors show that a different class of material (soft, transparent hydrogels) and a different mode of charge transport (ionic, rather than electronic) can yield electrodes with characteristics that are remarkably well suited for use in DEAs. A key but nonobvious realization is that even aqueous ionic hydrogels can deliver potentials of several kilovolts, despite the onset of water electrolysis at less than 1.5 V.

The physics is relatively simple. A potential applied to a conductor in contact with a hydrogel induces ionic transport that yields a net charge at the interface together with an adjacent screening charge, known collectively as an electric double layer. A cor-



**Thin, stretchy transparent actuators.** The hydrogel electrodes developed by Keplinger *et al.* carry current through ionic flow for use in soft, electrostatic actuators. In this artificial-muscle technology, sheets of hydrogels deliver large voltages to a dielectric elastomer. The applied potential creates electrical double layers that induce electrostatic forces to compress the elastomer. These deformations are well controlled, reversible, and capable of high-frequency operation. The resulting devices can be perfectly transparent, with potential for use in applications such as noise-canceling windows and display-mounted tactile interfaces.

---

Department of Materials Science and Engineering, University of Illinois at Urbana-Champaign, Urbana, IL 61820, USA. E-mail: jrogers@illinois.edu

responding charge appears at the interface with the dielectric elastomer (see the figure). The enormous difference between the capacitance of the double layer and the dielectric leads to a potential across the dielectric that can be millions of times greater than that across the double layer. As a result, potentials in the kilovolt range can be realized in the DEA without electrochemically degrading the hydrogel.

High-frequency actuation is also possible. Careful analysis shows that switching speeds in practical systems are limited only by mechanical inertia. Furthermore, because the stiffness of the hydrogel can be thousands of times smaller than that of the dielectric, actuation can occur freely, without mechanical constraint. These attractive characteristics are complemented by an additional, interesting feature: Hydrogels can have exceptionally high optical clarity across the visible range, thereby opening up a range of application possibilities enabled by transparent actuators.

The authors formed DEAs with this design simply by laminating films of polyacrylamide hydrogels formed with salt water onto the surfaces of dielectric elastomers. Such actuators can change their dimensions by nearly a factor of 2 and switch with millisecond speeds. As a demonstration, the authors built loudspeakers that produce high-fidelity sound throughout the audible range. The thin, planar geometries of these devices, taken together with their nearly complete optical transparency, foreshadow interesting applications such as active noise-canceling windows and display-mounted tactile interfaces. Adaptive optics represents another potential field of use. These and other prospects motivate the development of further refinements in the materials, including schemes to prevent drying of the hydrogels and methods to eliminate ionic build-up, hysteresis, and electrical shorting.

The success of ionic hydrogel conductors in DEAs hints at possibilities for their use in other unusual electrical systems, such as new classes of circuits and sensors that have elastic properties and shapes precisely matched to biological tissues for implants, surgical tools, and diagnostic systems that intimately integrate with the curved, dynamic external or internal surfaces of the body (*6*–*10*). Ionic hydrogels can offer favorable mechanics, and they can be biocompatible. Also, their operation exploits transport of ions, much like the intrinsic mode of electrical function in biological systems. Ionics, therefore, provides a natural type of biotic-abiotic interface.

Although the relatively slow speeds and the physical mass transport associated with ionic conduction preclude the general use of hydrogels as alternatives to metals in electronics, many possibilities can be considered. In fact, seminal experiments in the earliest days of semiconductor device research relied critically on ionic conductors to investigate field modulation of contact potentials in silicon and to enable the first solid-state amplifiers, as summarized in Bardeen's Nobel lecture in 1956 (*11*). Work in just the past 10 years has established the utility of similar electrolyte gate electrodes in printed and organic electronics (*12*). More recently, demonstration experiments showed that deformable ionic gels can serve as elements of high-performance, stretchable graphene transistors (*13*).

In the context of biomedical devices, related types of gels are already in widespread use for low-impedance interfaces between metal electrodes and the surface of the skin. One vision for system design might strategically combine both electronic and ionic modes of operation, in which the latter enables conformal electrical interfaces to biological tissues and provides soft mechanical actuation and sensing, whereas the former affords signal processing, control, acquisition, data storage, and transmission. Developing an associated base of fundamental knowledge in materials and device designs represents a promising direction for future work.

### References

1. R. E. Pelrine, R. D. Kornbluh, J. P. Joseph, *Sens. Act. A: Phys.* **64**, 77 (1998).
2. R. Pelrine, R. Kornbluh, Q. Pei, J. Joseph, *Science* **287**, 836 (2000).
3. C. Keplinger *et al.*, *Science* **341**, 984 (2013).
4. J. Zang *et al.*, *Nat. Mater.* **12**, 321 (2013).
5. S. Rosset, H. R. Shea, *Appl. Phys., A Mater. Sci. Process.* **110**, 281 (2013).
6. S. Wagner, S. Bauer, *MRS Bull.* **37**, 207 (2012).
7. J. A. Rogers, T. Someya, Y. Huang, *Science* **327**, 1603 (2010).
8. T. Someya, Ed., *Stretchable Electronics* (Wiley-VCH, Weinheim, Germany, 2013).
9. T. Sekitani, T. Someya, *Adv. Mater.* **22**, 2228 (2010).
10. D.-H. Kim, J. Xiao, J. Song, Y. Huang, J. A. Rogers, *Adv. Mater.* **22**, 2108 (2010).
11. J. Bardeen, in *Nobel Lectures, Physics 1942–1962* (Elsevier, Amsterdam, 1964), pp. 318–341.
12. S. H. Kim *et al.*, *Adv. Mater.* **25**, 1822 (2013).
13. S.-K. Lee *et al.*, *Nano Lett.* **11**, 4642 (2011).

10.1126/science.1243314

---

PSYCHOLOGY

# The Poor's Poor Mental Power

Poverty's mental toll might explain its connection to unhealthy impulsive behaviors.

**Kathleen D. Vohs**

Few people wish to be poor. Many find it puzzling that those in poverty seem to get stuck in that state, even when there are opportunities to improve one's lot. On page 976 of this issue, Mani *et al*. (*1*) provide a possible reason: Poverty-related concerns impair cognitive capacity. Simply put, being poor taps out one's mental reserves. This could explain data showing that the poor are likelier than others to behave in ways that are harmful to health and impede long-term success—in short, behaviors that can perpetuate a disadvantaged state.

The eye-opening study of Mani *et al.* included laboratory experiments and field studies that tested the "cognitive constraint" hypothesis. One experiment gave individuals who were poor (defined by household income) hypothetical financial decisions, followed by tasks that measured mental abilities. Poor people who earlier had contemplated a difficult financial decision showed worse mental performance than others. A study of farmers demonstrated that the mental acuities of the same person varied with swings in income. Farmers were given challenging cognitive tests before and after harvest. Before harvest, the farmers experienced much financial strain, whereas after harvest (and the receipt of payments), they did not. The results showed clear and demonstrable improvement in cognitive capacity after harvest. This outcome held after accounting for the stress of pre-harvest periods. The authors propose that poverty imposes a cognitive load, which impairs cognitive capacity.

The depletion of mental functioning with poverty comports with a framework called the limited-resource model of self-control. Failures of self-control are implicated in some of society's most pressing problems,

---

Marketing Department, University of Minnesota, 321 19th Avenue South, Minneapolis, MN 55455, USA. E-mail: kvohs@umn.edu

Published by AAAS

Science

# A Clear Advance in Soft Actuators

John A. Rogers

*Science* **341** (6149), 968-969.
DOI: 10.1126/science.1243314

---