New sensor enables 'smart diapers,' range of other health monitors

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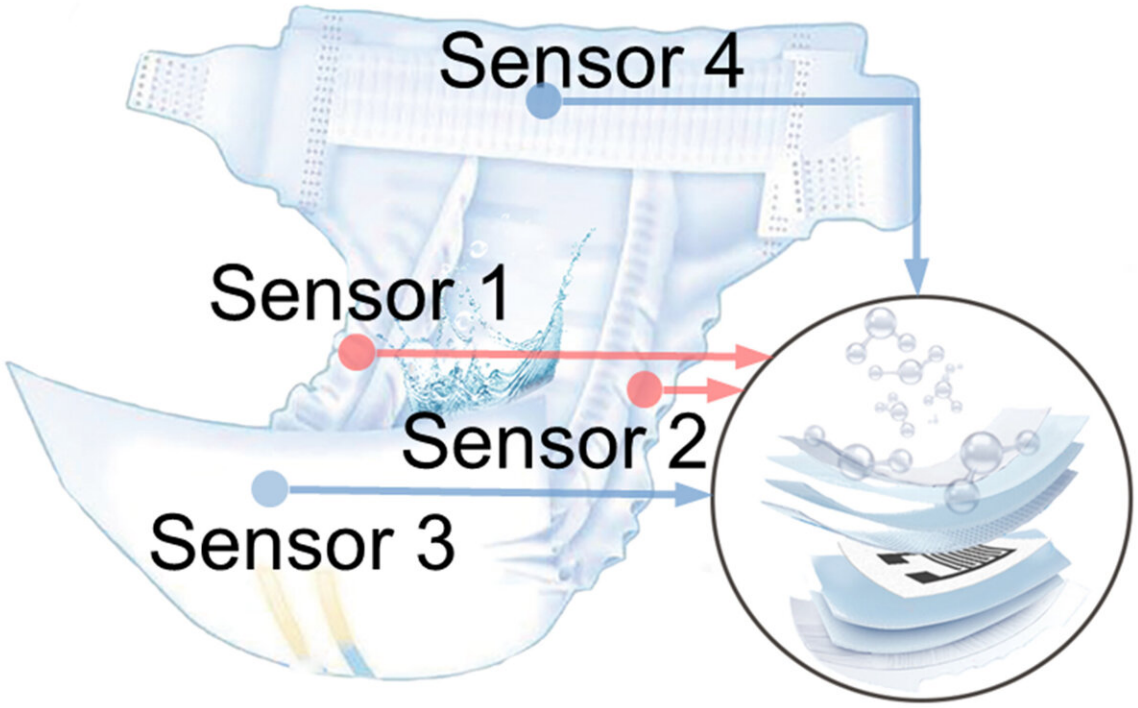

A Penn State-led research team integrated four humidity sensors between the absorbent layers of a diaper to create a "smart diaper," capable of detecting wetness and alerting for a change. Credit: Huanyu "Larry" Cheng/Penn State

Waaahhh! While babies have a natural mechanism for alerting their parents that they need a diaper change, a new sensor developed by researchers at Penn State could help workers in daycares, hospitals and other settings provide more immediate care to their charges.

The new sensor—so cheap and simple to produce that it can be hand-drawn with a pencil onto paper treated with sodium chloride—could clear the way for wearable, self-powered health monitors for use not only in "smart diapers" but also to predict major health concerns like cardiac arrest and pneumonia.

"Our team has been focused on developing devices that can capture vital information for human health," said Huanyu "Larry" Cheng, the James L. Henderson, Jr. Memorial Associate Professor of Engineering Science and Mechanics at Penn State. "The goal is early prediction for disease conditions and health situations, to spot problems before it is too late."

Cheng is the lead author on a new study, published in the journal *Nano Letters*, which describes the design and fabrication process for a reliable, hand-drawn electrode sensor. The sensor is created using a pencil, drawn on paper treated with a sodium chloride solution. The hydration sensor is highly sensitive to changes in humidity and provides accurate readings over a wide range of relative humidity levels, from 5.6% to 90%.

Research into wearable sensors has been gaining momentum because of their wide-ranging applications in medical health, disaster warning and military defense, Cheng explained. Flexible humidity sensors have become increasingly necessary in health care, for uses such as respiratory monitoring and skin humidity detection, but it is still challenging to achieve high sensitivity and easy disposal with simple, low-cost fabrication processes, he added.

"We wanted to develop something low-cost that people would

understand how to make and use—and you can't get more accessible than pencil and paper," said Li Yang, professor in the School of Artificial Intelligence at China's Hebei University of Technology. "You don't need to have some piece of multi-million-dollar equipment for fabrication. You just need to be able to draw within the lines of a pre-drawn electrode on a treated piece of paper. It can be done simply and quickly."

The device takes advantage of the way paper naturally reacts to changes in humidity and uses the graphite in the pencil to interact with water molecules and the sodium chloride solution. As water molecules are absorbed by the paper, the solution becomes ionized and electrons begin to flow to the graphite in the pencil, setting off the sensor, which detects those changes in humidity in the environment and sends a signal to a smartphone, which displays and records the data.

Essentially, drawing on the pre-treated paper within pre-treated lines creates a miniaturized paper circuit board. The paper can be connected to a computer with copper wires and conductive silver paste to act as an environmental humidity detector. For wireless application, such as "smart diapers" and mask-based respiration monitoring, the drawing is connected to a tiny lithium battery which powers data transmission to a smartphone via Bluetooth.

For the respiration monitor, the team drew the electrode directly on a solution-treated face mask. The sensor easily differentiated mouth breathing from nose breathing and was able to classify three breathing states: deep, regular and rapid. Cheng explained that the data collected could be used to detect the onset of various disease conditions, such as respiratory arrest and shortness of breath and provide opportunities in the smart internet of things and telemedicine.

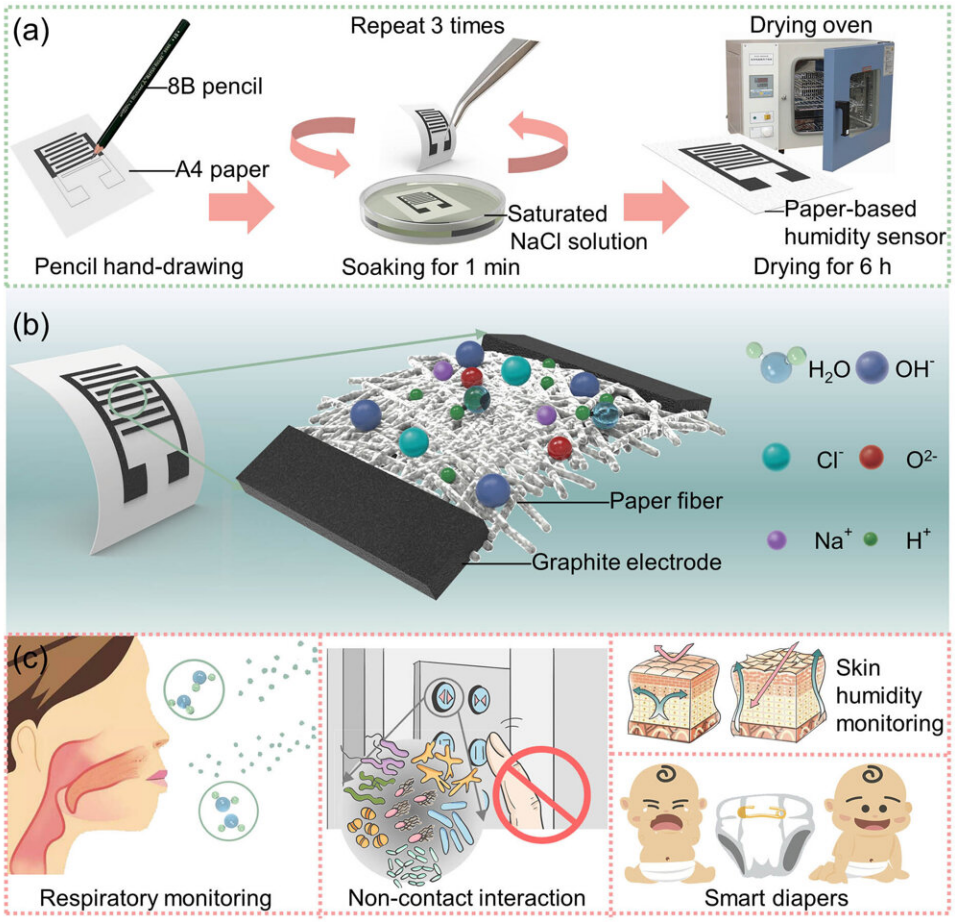

Illustration showing fabrication and application of the pencil-on-paper hydration sensor. Schematics showing the (a) fabrication processes and (b) the response mechanism of the flexible pencil-on-paper hydration sensor with (c) applications in health monitoring, noncontact switching, and skin characterizations. Credit: Huanyu "Larry" Cheng / Penn State

He added that respiratory rate is a fundamental vital sign and research has shown it to be an early indicator of a variety of pathological conditions such as cardiac events, pneumonia and clinical deterioration. It can also indicate emotional stressors like cognitive load, heat, cold, physical effort and exercise-induced fatigue.

Compared with breath, the human skin exhibits a smaller change in humidity, but the researchers were still able to detect changes using their pencil-on-paper humidity sensor, even after test subjects applied lotion or exercised. Skin is the body's largest organ, Cheng explained, so if it is not processing moisture correctly, that could indicate that some other health issue is going on.

"Different types of disease conditions result in different rates of water loss on our skin," he said. "The skin will function differently based on those underlying conditions, which we will be able to flag and possibly characterize using the sensor."

The team also integrated four humidity sensors between the absorbent layers of a diaper to create a "smart diaper," capable of detecting wetness and alerting for a change.

"That application was actually born out of personal experience," said Cheng, who is the father of two young children. "There's no easy way to know how wet is wet, and that information could be really valuable for parents. The sensor can provide data in the short-term, to alert for diaper changes, but also in the long-term, to show patterns that can inform parents about the overall health of their child."

The applications of the humidity sensor go beyond "smart diapers" and monitoring for respiration and perspiration, Cheng explained. The team also deployed the sensor as a noncontact switch, which could sense the humidity changes in the air from the presence of a finger without the finger touching the sensor. The team used the noncontact switch to operate a small-scale elevator, play a keyboard and light up an LED array.

"The atoms on the finger don't need to touch the button, they only need to be near the surface to diffuse the water molecules and trigger the

signal," Cheng said. "When we think about what we learned from the pandemic about the need to limit the body's contact with shared surfaces, a sensor like this could be an important tool to stop potential contamination."

More information: Guangyu Niu et al, Pencil-on-Paper Humidity Sensor Treated with NaCl Solution for Health Monitoring and Skin Characterization, *Nano Letters* (2022). DOI: 10.1021/acs.nanolett.2c04384

Provided by Pennsylvania State University