HEALTHCARE ELECTRONICS

Soft sensors form a network

A wearable wireless sensor network for personalized healthcare can be created through the indirect integration of soft on-skin sensors and rigid in-clothes circuits.

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Electronics based on soft and stretchable materials are able to interface with complex and nonplanar surfaces, leading to devices that can follow the contours of the human body. Such devices could play a valuable role in the development of data-driven personalized healthcare, and substantial effort has been focused on exploring intrinsically soft materials and optimizing deformable structures[1,2]. However, when subject to strain, devices made purely of soft materials often lack the performance stability of their rigid counterparts due to the unavoidable piezoresistance effect of these materials. As a result, soft and rigid materials are normally integrated, typically in an 'island–bridge' layout, in order to provide capabilities and functionalities comparable to conventional rigid silicon electronics. However, sophisticated functionalities, such

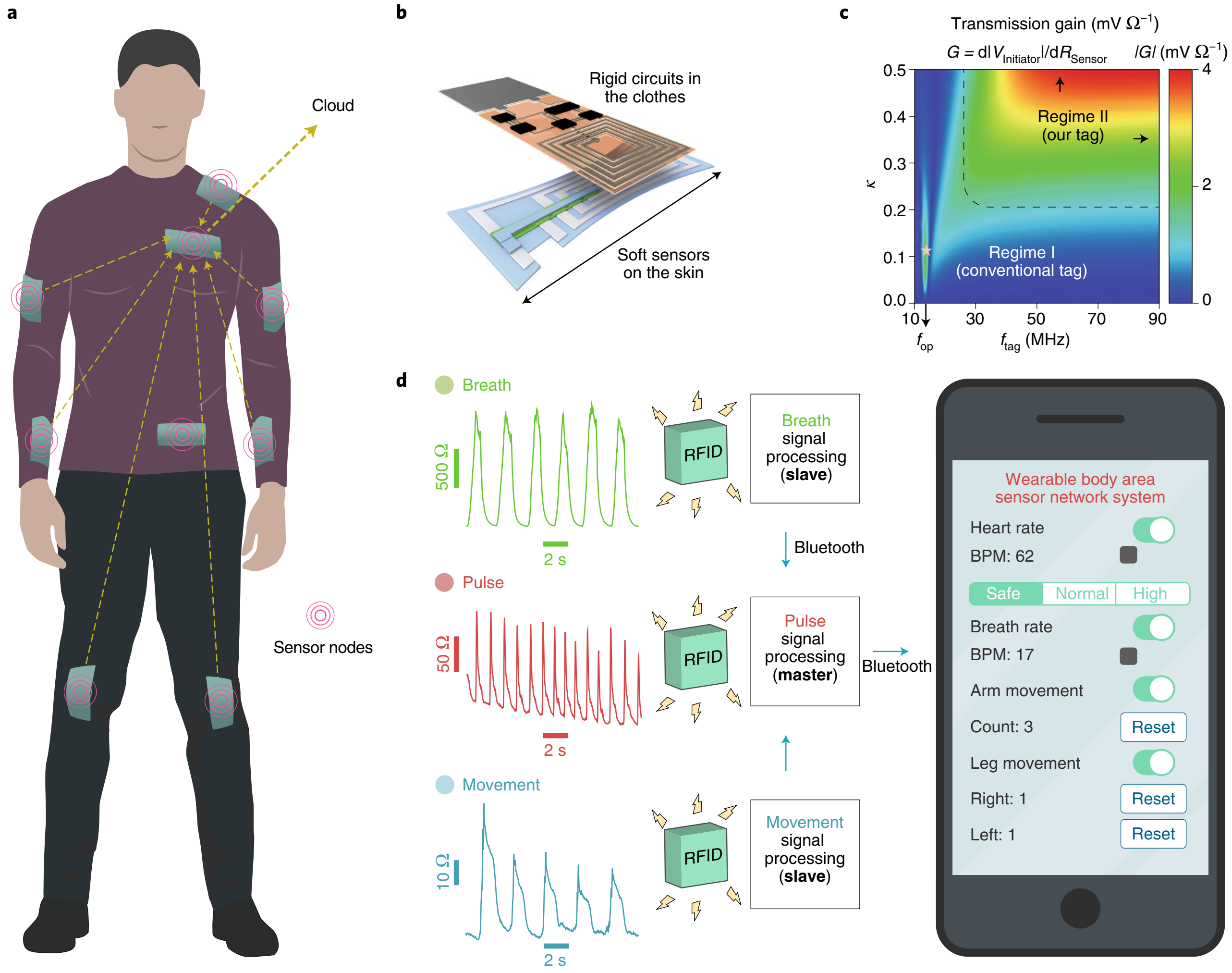

Fig. 1 | **A body area network based on soft sensor nodes. a**, Concept of the sensor network. **b**, Illustration of the sensor node, including the separated soft sensor tag on the skin and the rigid read-out circuit in the clothes. **c**, Influence of the antenna frequency and coupling factor on the transmission gain. f_{tag}, target resonant frequency; κ, coupling factor between the initiator and target inductors; f_{op}, operation frequency (fixed at 13.56 MHz). **d**, Simultaneous recording, wireless transmission and smartphone display of the physiological signals. Credit: adapted from ref. [6], Springer Nature Ltd as synchronized monitoring[3] and wireless communication[4,5], require the use of rigid commercial-off-the-shelf chips for a high integration density, and the incorporation of rigid chips requires advanced engineering to minimize strain concentration at the integration sites. Thus, a design dilemma exists in balancing the device functionality and mechanical performance. Now, writing in *Nature Electronics*, Xiaodong Chen, Zhenan Bao and colleagues show that soft on-skin sensors and rigid in-clothes read-out circuits can be indirectly integrated by using radio-frequency identification technology to wirelessly couple them[6]. By distributing an array of these sensor–circuit pairs across a person's body, a sensor network for personalized healthcare can be created.

The researchers — who are based at Stanford University, Nanyang Technological University and the Samsung Advanced Institute of Technology — designed a body-area wireless sensor network that consists of multiple stretchable sensor tags and rigid/flexible read-out circuits. The skin-mounted sensor tags are fabricated by printing intrinsically stretchable materials onto elastic substrates to form functional strain sensors and antennas. The read-out circuits are built with rigid commercial off-the-shelf chips, which can be attached to clothes. The combination of a sensor tag and read-out circuit serves as a sensor node in the network. The body area sensor network consists of multiple sensing nodes at different body parts for detecting breath, pulse and joint movement (Fig. 1a). The signals recorded from the nodes are sent to a smartphone via Bluetooth, and then to the cloud for storage or further analysis. The success of this sensor network lies in the physical separation of the sensor tags from the read-out circuits (Fig. 1b) — rigid chips are separated from the stretchable tags, which avoids potential strain concentration induced by direct integration.

The on-skin sensor tag contains three passive components: an inductor, a capacitor, and a resistive strain sensor. When subject to 50% strain, the inductance increases by ~30%, the capacitance increases by ~85%, and the resistance increases by ~2,000 times due to the high sensitivity and low initial resistance of the strain sensor. As a result, the device resonant frequency decreases by ~34%, and the quality factor decreases by ~91%. To achieve reliable wireless read-out with such dramatic electronic property change, the researchers explored an unconventional detuned coupling condition. First, by finely adjusting the three passive antenna components, they shifted the tag frequency from 13.56 MHz to over 30 MHz, while keeping the resonant frequency of the in-clothes antenna at 13.56 MHz. Second, by decreasing the working distance between the two antennas, they increased the coupling factor from 0.1 to over 0.2. Therefore, the coupling condition of the two antennas was moved from the regime of a conventional tag (regime I; Fig. 1c) to an alternative regime (regime II; Fig. 1c). Although the first regime is the ideal coupling condition for rigid antennas and offers the highest transmission gain, it has a small tolerance to the changes of antenna properties, such as the frequency and the coupling factor. The alternative regime is a good choice for soft antennas, as the tolerance of soft antennas to electronic property changes is greatly increased in comparison to rigid antennas.

The integrated read-out circuit serves as the initiator component of the sensor node. It allows simultaneous transmission of the acquired body area physiological signals. To transmit these signals in a synchronized manner, one of the sensor nodes is selected as the master node to coordinate the data transmission, and the others work as slave nodes to feed measured data to the master node. Once the data from the slave nodes is gathered, the master node sends all collected data to a smartphone via Bluetooth (Fig. 1d). Finally, the data can be transmitted to the cloud server through the cellular network.

The body area sensor network developed by Chen, Bao and colleagues, which is based on indirect soft–rigid component integration, provides a new solution for robust and reliable monitoring of human vital signals. For future development of this technology, additional computing power may be implemented in the sensor node. Although challenging to achieve, the distributed computing capability is the key to guaranteeing long-term viability for this technology, especially for future use in personalized healthcare. Furthermore, diversifying intrinsically soft sensors beyond strain sensing, such as optical[7], chemical and biological sensors[8], could significantly expand the toolbox and broaden the impact of the platform. Though work remains to be done, this sensor network represents an important step towards the next generation of wearable electronics and, more broadly, the 'Internet of Medical Things'. ❐

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References

1. Rogers, J. A., Someya, T. & Huang, Y. *Science* **327**, 1603–1607 (2010).
2. Wang, C., Wang, C., Huang, Z. & Xu, S. *Adv. Mater.* **30**, 1801368 (2018).
3. Gao, W. et al. *Nature* **529**, 509–514 (2016).
4. Huang, Z. et al. *Nat. Electron.* **1**, 473–480 (2018).
5. Bandodkar, A. J. et al. *Sci. Adv.* **5**, eaav3294 (2019).
6. Niu, S. et al. *Nat. Electron.* https://doi.org/10.1038/s41928-019-0286-2 (2019).
7. Yokota, T. et al. *Sci. Adv.* **2**, e1501856 (2016).
8. Kim, J., Campbell, A. S., de Ávila, B. E. F. & Wang, J. *Nat. Biotech.* **37**, 389–406 (2019).