in many countries where health care is unregulated[19].

Systems of accreditation for cancer centres (public and private) could also help to ensure that institutions offer interventions only after demonstrating competence and achieving certain scores from patient feedback and peer review. They may also encourage the establishment of specialist centres. Data from the past 25 years have shown that cancer patients do much better if the surgeon treating them has operated on many others with the same condition as part of a multidisciplinary team[20].

Cancer 'moonshots' may improve individual outcomes in high-income countries with strong governance, but they will not solve the rising economic and social burden of cancer globally. What we need are 'earthshots' that focus on building infrastructure and delivering affordable, equitable and effective care. ■

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Unobtrusive 'elastronic' transistors can behave like skin and stretch without tearing.

AMIR FOUDEH, JIE XU, SIHONG WANG AND ZHENAN BAO

Bring on the bodyNET

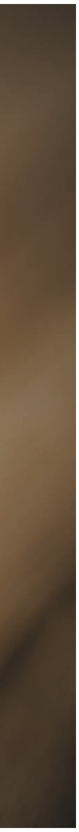
Stretchable sensors, circuits and batteries are about to change our relationships with electronics and each other, explain **Bryant Chu** and colleagues.

Electronics are set to merge with our bodies to extend our perceptions. Smartphones and watches will give way to the bodyNET[1]: a network of sensors, screens and smart devices woven into our clothing, worn on our skin and implanted in our bodies (see 'Superhuman powers'). A pregnant woman might wear tiny biometric sensors to monitor her baby's heartbeat, displayed on a film attached to her skin. She could transmit its kicks to the father wirelessly, so that he can experience the vibrations recreated by 'haptics' — interfaces that provide tactile feedback — on his stomach.

The bodyNET is not yet complete, and labs around the world are developing its components. The core technology is electronics that stretch — elastronics — made from soft plastic circuits thinner than paper that can deform without tearing, biodegrade and even heal themselves (see go.nature.com/2vtutzz). Elastronic sensors respond to touch, pressure, temperature, humidity and light, as well as to chemical and biological signals[2–10].

There is much still to do. Researchers must improve the technical performance of elastronic materials, design innovative architectures for stretchable circuits and drive down costs through mass production. There are also social and cultural concerns. These include widespread fears of merging technology intimately with the body, as well as anxieties about privacy and data security.

Yet we are optimistic that the benefits of bodyNETs will outweigh the challenges. These extensions of ourselves will allow us to sense and communicate with others and our surroundings in new and sophisticated ways, beyond our existing five senses. Being able to see how a patient is feeling in real time, or



whether a loved one is in need of emotional support, could make us more aware and empathetic. Rather than replacing us, such technology will extend our human qualities.

For example, augmented-reality cosmetics or decorative displays on the body could change colour to indicate our mood. Digital tattoos, powered by batteries in clothing, could reveal our emotions through biometric data relating to posture, imperceptible facial expressions, heart rate and skin conductivity. Flight information could be displayed on glasses as you look up at a plane. Or imagine being able to respond remotely to health alerts about a child's emergency.

Here we highlight research priorities for the bodyNET.

EIGHT TECHNICAL CHALLENGES

Materials. Electronic components that behave much like skin need to be developed. The conductivity of stretchable polymer semiconductors and conductors must match that of rigid ones. Biocompatible substrates need to become more durable so that they can be worn on the skin for months. These materials will have to survive sweating, bathing and normal wear and tear, as well as washing cycles if incorporated into clothing.

Circuits. New designs for stretchable circuits are needed. These must compensate for electrical properties that change when the components are distorted. They must be made thinner and cheaper to fabricate. Processes for manufacturing circuits using elastronic materials are underdeveloped and often involve many steps, resulting in low final yields. It is hard to achieve high precision by aligning layers using shadow masks, for example; and most printing methods can pattern materials at low resolution only, thus limiting the speed of the circuits.

Sensors. Skin-like devices that can measure pressure, strain and temperature, as well as the presence and level of certain chemicals, need to be developed further to monitor body movements and health conditions. Changes in temperature and pressure, in particular, are hard for sensors to separate, because each affects the other. Some sensors have been prototyped using stretchable conductors, semiconductors and (charge-holding) dielectric materials, but solving the problem will require new types of circuit.

Energy storage and harvesting. Stretchable batteries must become smaller and more efficient, providing weeks of use. Battery electrodes made from stretchable materials, such as polymer and inorganic composites, are bulkier than coin batteries of similar power. And batteries that stretch mechanically, using moving components, suffer from wear and tear. Energy-harvesting strategies, too, are limited. Piezoelectric generators that harvest energy from motion provide only spikes of low power. Thin-film solar cells capture energy from sunlight but are ineffective under clothing. Flexible thermoelectric materials are not yet good enough to collect useful amounts of power from body heat.

Modelling. Advanced simulation techniques will help researchers to design complex elastronic circuits and architectures. Being able to test many designs before fabrication would lower the cost of prototyping. For example, mathematical models of molecules and materials will predict electrical properties and mechanical behaviour such as crack propagation under extreme stretching.

Mass fabrication. Elastronics are currently made only in small quantities in research labs. Mass-production techniques, such as roll-to-roll coating, patterning and printing, would reduce the cost and increase the reliability of the circuits. New materials require years of development before they can be commercialized. It took the semiconductor industry decades to evolve high-speed, high-performance mass manufacturing, and a similar process is needed to produce elastronics at scale.

Peripherals. Shifting communications technologies from separate devices, such as smartphones, to integrated devices on the body will make our interactions with them more natural. This trend has begun with wearables such as the Samsung Gear and the Apple Watch, but these are still limited in function. Elastronics on the skin would offer entirely new 'superpowers' through touch-sensitive haptic devices, thin and stretchable displays, gesture-based controls and audio systems that stay on the body indefinitely. Mixed-reality devices networked to the bodyNET that allow you to remotely interact with other people and objects need to be developed.

"Digital tattoos, powered by batteries in clothing, could reveal our emotions."

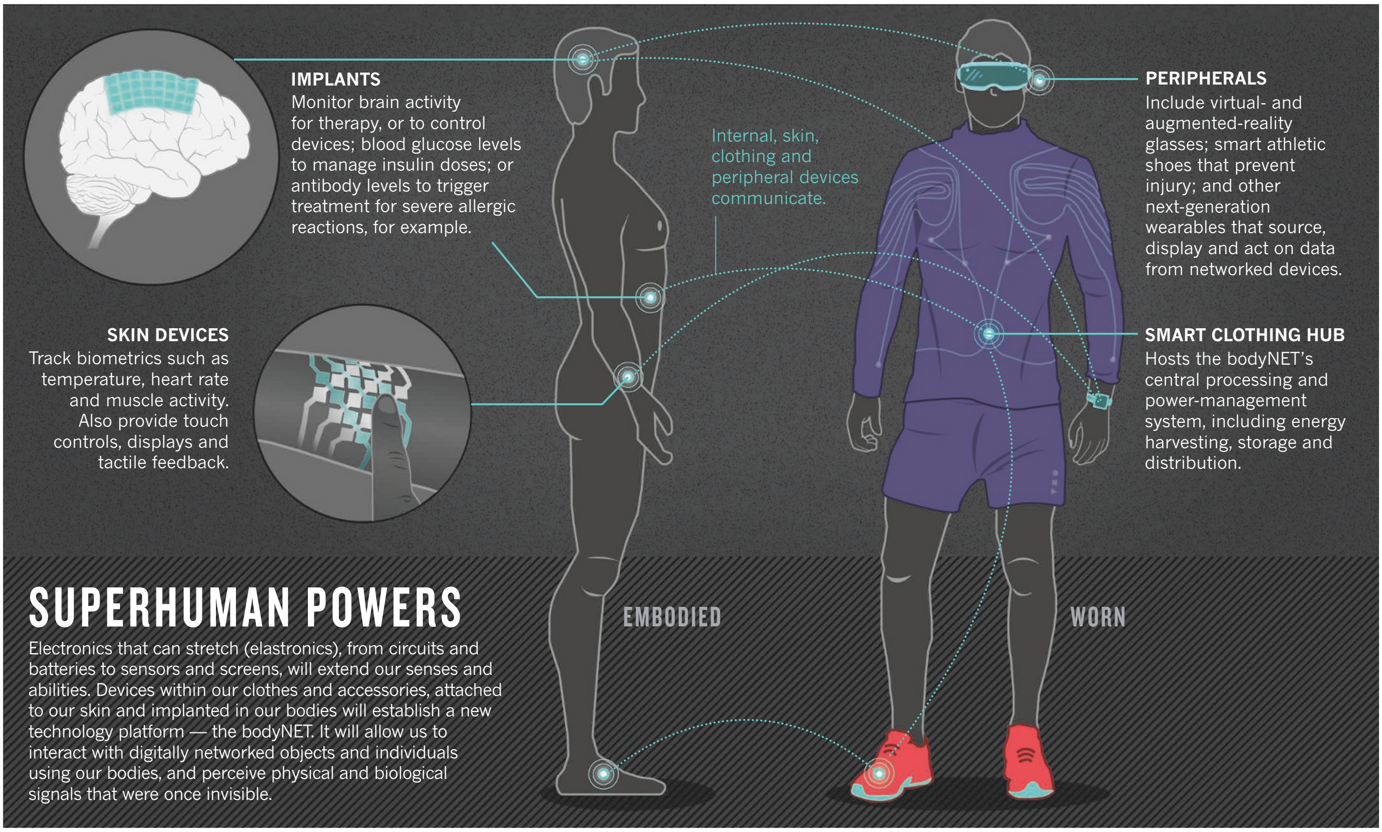
Digital communication. BodyNETs will require a digital communications network to connect their layers, and this is yet to be built. It must bridge the digital and physical worlds between individuals, objects and environments. Data must be transmitted reliably across implants, skin sensors, devices embedded in clothing and those packaged as peripherals, as well as from one person's bodyNET to another's. Built spaces could become personalized, with room conditions controlled by skin temperature and perspiration, lighting by circadian rhythm, and furniture by body size and muscle activity. People who speak different languages could soon communicate using real-time translation, emotion tracking and dynamic augmented-reality graphics.

FIVE CULTURAL CHALLENGES

Human needs. Translating data into useful forms rooted in human needs will be essential. Our interviews with users of wearables revealed that raw data — blood pressure, pulse or galvanic skin response, for example — are of little use unless they prompt an action or are applied to improve lives, by alerting users to potential heat stroke on a warm day, for instance. Users who tested being able to track emotions with virtual-reality mock-ups said they valued being able to empathize more easily with others, especially in high-stakes situations such as mitigating work disagreements and clearing up cross-cultural confusion. The full potential of bodyNETs will be harnessed through global networks, and different sociocultural ecosystems must be factored into designs.

Body modification. The relationship between technology and the body needs to be considered. We must reframe fears and preconceptions. The only types of body modification accepted by most people today are those achieved by medical and restorative procedures such as joint replacements. Artificial intelligence often incites a fear of the unknown, and combining living tissue with electronics provokes aversion. We think that this mentality will shift as public knowledge increases, elastronics that work with the body advance, and human-centred applications such as continuous, personalized health care — rather than novelties — begin to improve daily life. Medicine and communication are two paths forward. Long-term treatments such as insulin dosing can be revolutionized by replacing existing devices with networked, biocompatible ones that conform to the body's tissues. Body decoration is also increasingly accepted. Its long history could continue, with elastronics serving as a new medium for expression as well as performing technical functions.

Data security. Data privacy and security are essential. Medical and health and wellness data must remain individual property. Fitness trackers have been criticized for having confusing and vague privacy policies that potentially allow third-party sharing of health information. BodyNETs would face the same challenges. This is not a new issue. Sharing credit-card information was unheard of, until online shopping drove the development of security protocols and users gained trust in the process. Similarly, bodyNET technology must be secured from potential attacks and used for applications



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that improve the lives of its users. Legal structures must be created to ensure that use of this technology requires consent, and that it is not exploited for malicious purposes, such as denying healthcare on the basis of diet, selling data for profit, or worse.

Data influence. Biometric information gained through sensors influences behaviour and can have unintended consequences. It is crucial that measurements are robust. Inaccurate data can lead, for example, to medical emergencies being missed, or flagged incorrectly. In 2016, a lawsuit was filed against Fitbit, a manufacturer of wearables, over the accuracy of its heart-rate measurements. Decisions to design such devices for health purposes will need to be made carefully, recognizing that users might operate devices for health monitoring regardless of recommendations. As biometrics are developed further, the complexity of devices will increase, as will the chance of error. So it is important that procedures for debugging bodyNETs are formalized. Our group is exploring acquiring data with pairs of sensors to increase accuracy.

User interaction. More must be learnt about how to present bodyNET data effectively, both visually and physically. Should invisible emotions be represented by a colour-changing glow around an individual, an animal avatar, or something else? Hardware and software interfaces need to be designed with user interaction as a priority. BodyNETs will allow us to use our natural embodied intelligence to experience the data-rich world in completely new ways.

NEXT STEPS

We think that the business landscape for elastronics could eventually resemble that for printed circuit boards. Dedicated elastronic circuit manufacturers will fabricate components for large system-integration and digital-communications companies. These large companies would develop their own commercial devices or sell components to start-ups that produce their own devices.

Applications for the first bodyNETs must be developed now. Initial devices will probably be simple but reliable systems of biometric sensors that display information in an actionable way. For example, a stretchable 'sleeve' might display a person's mood or comfort level. Later versions would be more complex, and could include augmented-reality glasses powered by elastronics embedded in clothing.

Social-science studies will be crucial to understanding the short- and long-term impacts of these new forms of interactions, and to exposing unintended consequences. We must develop the bodyNET system responsibly, mindful of its repercussions. Multidisciplinary partnerships should be created, and governments must develop privacy and regulatory legislation.

The bodyNET's disruptive potential is great. Conversations must start now to ensure that we create the best possible version, both technically and ethically, of this transformative technology. ■

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