Check for updates

Shaping the future of robotics through materials innovation

New classes of functional soft materials show promise to revolutionize robotics. Now materials scientists must focus on realizing the predicted performance of these materials and developing effective and robust interfaces to integrate them into highly functional robotic systems that have a positive impact on human life.

Philipp Rothemund, Yoonho Kim, Ronald H. Heisser, Xuanhe Zhao, Robert F. Shepherd and Christoph Keplinger

We are in the middle of a robotics revolution; robots have already transformed manufacturing in many industries such as automotive and electronics, and now we are seeing attempts to bring them into our daily lives. Simple robots such as autonomous vacuum cleaners and lawn mowers are already affordable by individual consumers, and we expect that more complex robots will become available in the future. Robots will assist in the care of the sick and elderly and will collaborate with us in our workplace and in situations that are too dangerous for humans, such as after a natural disaster (Fig. 1). We will integrate robotic components with our bodies, be it through exoskeletons that enhance the capabilities of the human body or lifelike active prostheses that are directly interfaced with our nervous system and controlled by the human brain. Many of these applications will benefit from advances in controls and machine learning, but virtually all will require new types of robot bodies. This Comment discusses why and how materials science — and in particular functional soft materials — will play a key role in shaping the future of robotics.

Today, a typical robot consists of hard materials such as metals or rigid plastics and is driven by electromagnetic motors. Materials science has greatly contributed to the success of these robots in industry by developing materials that make them stronger, lighter, stiffer and more precise. However, only few examples exist in which robots have left the factory floor, because operating in unstructured environments requires a level of versatility and adaptability that is difficult to achieve with typical robots based on hard materials — we believe that these intrinsic problems can only be overcome with new types of adaptable, compliant robot bodies and new control concepts supported by machine learning. Some problems — such as seamlessly interfacing the human body with a lifelike active prosthesis — can only be solved by using functional soft materials. We, therefore, believe that the future of robotics is (at least partially) soft, and that materials science will be at the core of robotics innovation.

Whereas humans have used and optimized metal alloys for tools and machines for thousands of years, the industrial use of soft materials (in the form of natural rubber) has only begun in the nineteenth century, and so these materials are in an earlier stage of their development. The introduction of synthetic rubber during World War II has led to a drastic increase in the mechanical performance of soft materials. In the past decades, a large number of functional materials have been developed that are not only soft but can also react actively to different types of stimuli (for example, coiled polymer fibres that contract when heated, elastomers that deform in response to magnetic fields)[1,2]. In parallel, innovations in materials chemistry and processing have led to new manufacturing techniques that can produce previously unfathomable geometries in minutes or hours; additive manufacturing (for example, 3D printing) has become core to robot design strategies as it can be used to prototype complex parts, but also to directly fabricate robots consisting of multiple different and functional materials.

With these new classes of materials and manufacturing tools, materials science is now in a position to play a key role in enabling the future of robotics. Materials scientists have already shown that soft materials can be used to design grippers that grasp fragile objects of various shapes without feedback control[3,4], that materials can autonomously generate and control motion without using electronics[5–7], and that functional soft materials can perform tasks at microscopic scales[2,8], thereby demonstrating that materials innovations can enable functions that are impossible to achieve with traditional hard robots. However, based on the ample research experiencethat we have gained in our academic laboratories and in our start-up companies over the past years, we have learned that only by building fully functional robotic systems that solve practical problems does one realize the important fundamental materials science questions that still need to be answered. Importantly, materials scientists in academic research labs should go far beyond proof-of-principle demonstrations of new promising materials and working principles; trying out entirely new ideas will also in the future lead to revolutionary technologies, but without also focusing on solving practical problems, we risk seeing functional soft materials remain mostly an academic discipline, which is likely to disappear into oblivion[9].

We have identified two main problems that currently stand in the way for functional soft materials to make a wide impact in robotics. First, while many emerging technologies based on functional soft materials have the potential to substantially surpass the performance of established technologies, they currently only achieve fractions of their predicted performance and are therefore either not yet attractive enough to find their way into commercial systems or capable enough to enable revolutionary new types of robotic systems. Second, functional soft materials are typically demonstrated only as stand-alone components. However, they often cannot fully exploit their potential when used in a robotic system due to missing or unreliable interface technologies. Creating reliable interfaces between robotic systems based on functional soft materials and their environment and between individual components inside such systems is a substantial research challenge, because these components often exhibit vastly different properties and functions using different physical stimuli. For the

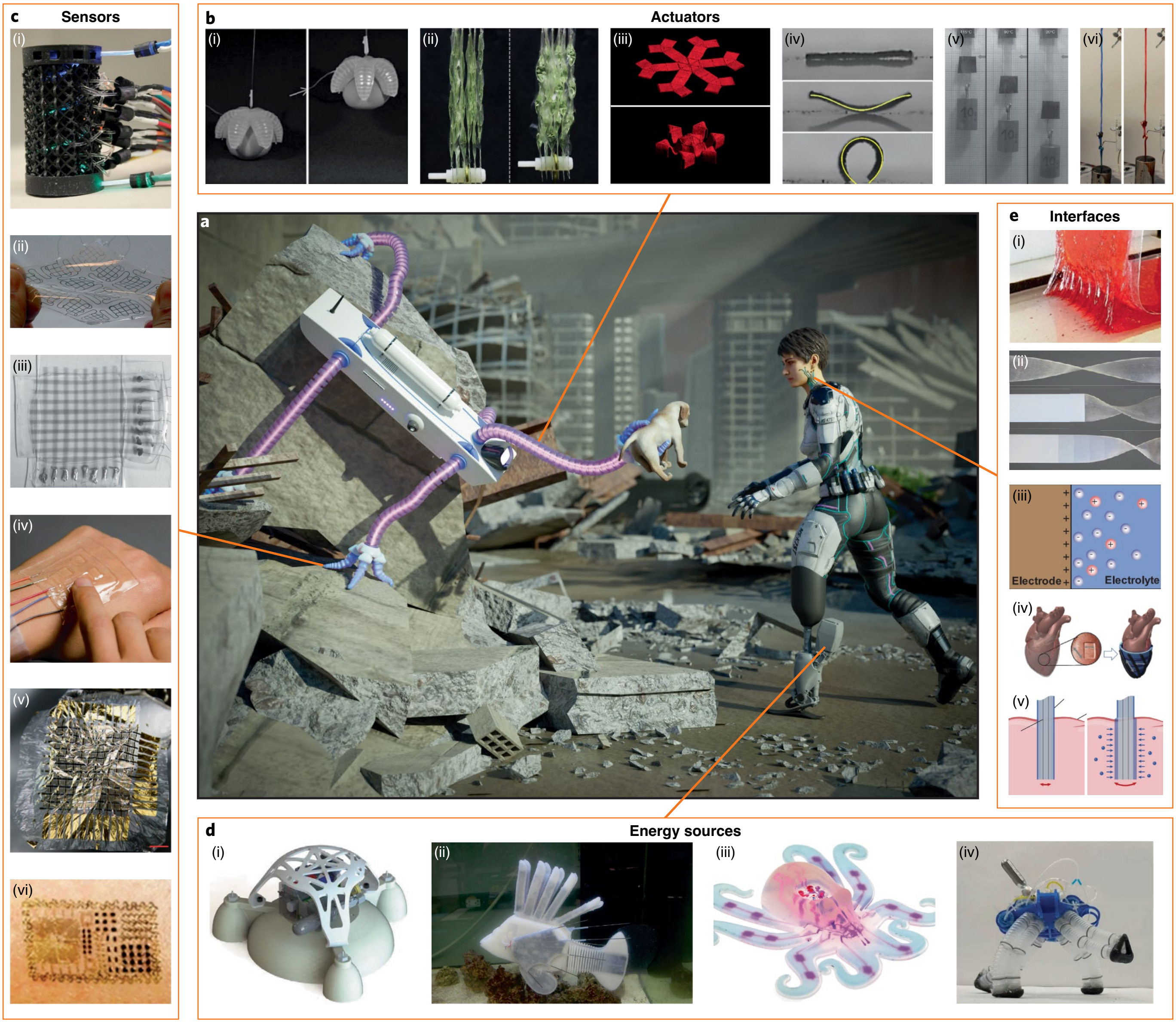

Fig. 1 | Materials innovations that will shape the future of robotics. a, In the future, robots will autonomously navigate difficult terrains, closely collaborate with people and support them in dangerous tasks. Humans will be seamlessly integrated with robotic systems to enhance their physical capabilities or to restore them after injury. Most of these capabilities will require new types of functional soft materials, and thus materials scientists will play a crucial role in realizing this vision. **b**, Examples of technologies that show promise as soft actuators: pneumatic soft actuators[3] (i), electrohydraulic HASEL actuators[13] (ii), 3D-printed ferromagnetic soft actuators[11] (iii), small-scale magnetoelastic actuators[2] (iv), heat-responsive liquid-crystal elastomer actuators[12] (v), heat-responsive fibre-based artificial muscles[1] (vi). **c**, Examples of technologies that show promise as soft sensors: optical lace[18] (i), liquid-metal-based sensor skin[19] (ii), carbon-nanotube-based sensor skin[20] (iii), ionic skin[21] (iv), imperceptible electronics[22] (v), epidermal electronics[23] (vi). **d**, Examples of technologies that show promise as energy sources for untethered robots: combustible gases[39] (i), electrolytic flow-batteries[26] (ii), catalytic decomposition of fuel into gas[6] (iii), compressed air[27] (iv). **e**, Examples of interfaces of functional soft materials: hard–soft interface[38] (i), interface with stiffness gradient[39] (ii), ionic–electronic interface[40] (iii), interface between a soft actuator and the human body[33] (iv), electronics–brain interface[34] (v). Figure reproduced with permission from: **b**(i), ref. [3], Wiley; **b**(ii), ref. [13], AAAS; **b**(iii), ref. [11], Springer Nature Ltd; **b**(iv), ref. [2], Springer Nature Ltd; **b**(v), ref. [12], Wiley; **b**(vi), ref. [1], AAAS; **c**(i), ref. [18], AAAS; **c**(ii), ref. [19], IEEE; **c**(iii), ref. [20], Springer Nature Ltd; **c**(iv), ref. [21] Wiley; **c**(v), ref. [22], Springer Nature Ltd; **c**(vi), ref. [23], AAAS; **d**(i), ref. [39], AAAS; **d**(ii), ref. [26], Springer Nature Ltd; **d**(iii), ref. [6], Springer Nature Ltd; **d**(iv), ref. [27], AAAS; **e**(i), ref. [38], Springer Nature Ltd; **e**(ii), ref. [39], AAAS; **e**(iii), ref. [40], AAAS; **e**(iv), ref. [33], AAAS; **e**(v), ref. [34], under a Creative Commons license CC BY 4.0 (http://creativecommons.org/licenses/by/4.0/).

remainder of this Comment we will discuss how these two problems could be addressed, mainly focusing on representative areas in which we have gained comprehensive expertise through work both in our academic laboratories and start-ups. We are aware that there are many other important materials-related research topics as well as additional promising technologies relevant to robotics, but it would go beyond the scope of this Comment to provide a complete review of the entire field.

Realizing predicted performance

For functional soft materials to find uses in robotics, we must identify promising technologies that either provide completely new functions or that show potential (for example, by analysing their physical working principles) to substantially surpass the performance of traditional robotic components (Fig. 2). Even if in the early stages of development only a fraction of their predicted performance is realized, we expect that they will overtake traditional robotic components — which are already mature and have little room for further improvements — in the near future if materials scientists focus on the task at hand with the required rigour. This effort will require a strong synergy between fundamental research aimed at gaining a deeper understanding of new principles and applied research (for example, in collaboration with start-ups or industry) aimed at developing robotic systems based on these technologies that are able to tackle practical problems. In this context, we next discuss several examples in the areas of actuation, sensing and energy sources.

Actuators are core components of robotic systems. Many soft actuators have been developed that react to different types of physical stimuli including pressurized fluids[3], electric fields[10], magnetic fields[2,11] or heat[1,12] (Fig. 1b), opening new avenues for designing robots.

In 2018, we introduced a promising technology called hydraulically amplified self-healing electrostatic (HASEL) actuators (Fig. 1b(ii))[10,13]. These actuators use an electrohydraulic mechanism to generate motion that closely mimics the behaviour and performance of natural muscle, and they are, therefore, particularly well suited for bioinspired robotic systems where dynamic, lifelike, energy-efficient motion is a key requirement[14]. We have started to build various types of mobile and wearable robotic systems driven by HASEL actuators by interdisciplinary teams including collaborators from both academia and industry; these projects have highlighted that further substantial improvements of key performance metrics such as power-to-weight ratio and specific energy will open up entirely new fields of application. In parallel, we have analysed the fundamental actuation principles of HASEL actuators, which showed that their specific energy can, in principle, be improved from currently ~5 J kg^{-1} to above 10,000 J kg–1 (natural muscles exhibit up to 40 J kg–1; ref. [14])[15]. Realizing only a fraction of the predicted performance of HASEL actuators will revolutionize actuation across many areas of robotics, but these very high values currently cannot be achieved, because no materials system exists that simultaneously exhibits the necessary high electrical performance and high enough mechanical strength to sustain the occurring mechanical stresses. Among other challenges, developing such a materials system will require gaining a deeper fundamental understanding of the physical principles that govern the behaviour of solid–liquid dielectric composites under high electric fields[14]. For example, model calculations have shown that dielectric liquids inside HASEL actuators sustain electric fields that are multiple times larger than their reported dielectric breakdown strength[14,15], a phenomenon that we do not understand to date and that will become even more important in future HASEL actuators with substantially improved performance. Further, current HASEL actuators made from thermoplastic polymers exhibit a time-dependent reduction of the actuation strain that we hypothesize to be the result of interfacial charging[14]. Gaining a comprehensive understanding of these phenomena will require interdisciplinary collaborations that include chemists, electrical engineers and physicists.

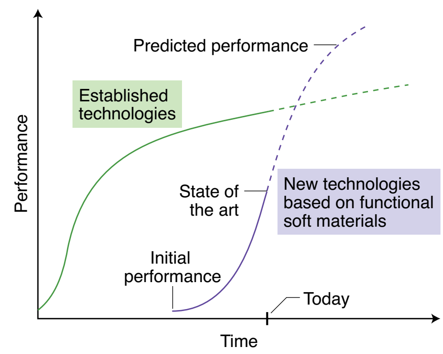

Fig. 2 | Realizing the predicted performance of emerging technologies. Many emerging technologies based on functional soft materials have the potential to substantially surpass the performance of established, already mature, technologies in robotics in the future (as indicated by the dashed lines), thereby enabling the design of entirely new types of robotic system. However, reaching very high values close to the predicted performance requires a concerted effort of the materials science community as well as a synergy between fundamental research in academia and applied research in industry.

Another example from our work and the work of others is magnetic soft actuators, which contain ferromagnetic particles that deform the material when exposed to magnetic fields (Fig. 1b(iii),(iv))[2,8,11]. Advanced fabrication methods have enabled the design of small-scale, magnetic soft robots with complex and programmable shape-changing capabilities[11,16] for applications in which conventional robots cannot be used due to miniaturization challenges. Magnetically controlled soft capsule robots, a few centimetres or millimetres in size, for targeted therapeutic delivery can roll under weak rotating magnetic fields and squeeze themselves to release drugs under a strong static field[17]. At sub-millimetre scales, magnetically steerable soft continuum robots can enable safer and quicker access to hard-to-reach areas in the complex vasculature of the brain for treating stroke or aneurysms[8]. These publications highlight the high potential of magnetic soft actuators and robots, but they also reveal that much work still needs to be done to make them practically useful for broader applications. Enabling more sophisticated functions requires increasing the level of complexity of both their programmed actuation patterns and the spatiotemporal control of the actuating field. For materials scientists, developing scalable and automated fabrication techniques to realize three-dimensional magnetization patterns for robots with more complex shapes will thus be an important area of future exploration. To turn their complex shape changes into dexterous manipulation, collective efforts will be needed to develop more robust and effective control strategies based on a data-driven approach for small-scale, magnetic soft robots, where traditional feedback control is largely inapplicable.

Flexible and stretchable sensors are another important area of research and development; future robots and prostheses will require high-fidelity information about the states of their structure, their actuators and their interaction with the nearby environment. The current paradigm of discrete, carefully placed sensors will not scale to meet these requirements. In contrast, functional soft materials allow the design of deformable, continuous arrays of sensors, which measure the state of the entire structure and provide an advanced form of proprioception. Promising examples include light-based sensors that can measure the deformation of a soft structure[18], stretchable sensors that measure strain and pressure[19,20], and electronic skins that measure various signals such as pressure, temperature or electrical signals (Fig. 1c)[21–23].

In 2018, we introduced deformable optical fibres embedded in a soft medium as sensors[24]. When illuminated, the intensity and colour of the output light and the coupling between fibres can be used to quickly detect changes in temperature, deformation and indentation over large surface areas (Fig. 1c(i))[18,24,25]. Even though we have already successfully used this technology to measure the deformation of soft grippers and to sense changes in muscle behaviour and health of high performance athletes, there is still ample room for improvement. Developing stretchable materials with lower optical impedance will allow for longer fibre lengths and light sources with lower energy consumption. Higher sensor precision can be achieved by introducing optical elements directly into the fibre core and cladding, or by varying shape at fibre coupling locations. Lastly, self-healing materials can be incorporated into the sensor system to help repair or extend functional lifetimes of robots operating in the field.

Energy storage is a critical issue for any type of mobile robot (Fig. 1d). The capacity of the energy source determines the operational time, the distance it can travel and the work it can do. Materials science is at the core of developing safe, portable energy sources with higher power and energy densities. Functional soft materials have enabled completely new concepts for the storage and use of energy inside the body of a robot[6,26–28]. For example, chemical fuel can simultaneously drive and control the motion of a fluidic soft robot[6]; elastic energy stored in a swollen hydrogel can be used to generate fast, oscillatory deformation[29].

We have demonstrated an integrated approach to energy storage at high energy density by combining energy storage, actuation and force transmission into one electrolytic, hydraulic, soft actuation system (Fig. 1d(ii))[26]. The redox flow battery system design enabled a robotic fish to operate up to 36 hours, but the demonstrated prototype exhibited a low power density. The potential for this form of embodied energy storage can be seen in our own bodies. The human body efficiently stores energy in the form of fat throughout the entire body. Glucose, distributed through the cardiovascular system, provides the brain and muscles with energy, which in turn drives the body, including the cardiovascular system. Fuel cells, while architecturally similar to redox flow batteries, offer substantially higher energy densities and could potentially enable long-duration missions. Liquid ammonia has recently been studied as an alternative to hydrogen due to its transportation stability, carbon-free operation and mass production. Realizing such systems in soft robots, however, requires new materials systems that can withstand accompanying high temperatures and maintain catalyst and electrode placement.

Creating reliable interfaces

Designers of traditional robots can rely on standardized interfaces (for example, mechanical fasteners, electrical connectors) to integrate individual components into a robot body, but also to interface a robot with its environment. For functional soft components, standardized interfaces do not exist yet; if we want to use them in practical robotic systems we must begin developing the necessary interfaces. Therefore, materials scientists must think about the materials that future systems will consist of, and the way those materials will interact and interface with each other when integrated into a larger robotic framework. With a more mature fundamental science established, we can offer robot designers a new suite of manufacturing and assembly techniques to put these materials to work in commercially viable robotic, biomedical and consumer products.

A typical robot consists of components such as energy sources, actuators, sensors, structural elements and components that handle computation and communication (Fig. 3). Even though a single functional soft material may assume the function of multiple traditional robotic components, interfaces will remain an integral part of a robot. Interfaces between components inside the robot must provide a strong, reliable mechanical connection and enable transmission of information and energy between components. Materials scientists must additionally find ways to functionally connect materials that use different physical stimuli (electric field, heat, light, and so on). Further, functional soft materials offer new ways for robots to interact with their surroundings, including handling of objects[3,30], to interact with other machines, to integrate onto the human body[31–33] and to interface with the human nervous system[34,35]. The development of reliable interfaces will undoubtedly require the collaboration of researchers of different fields of materials science. Below, we highlight some exemplary challenges of developing interfaces for functional soft materials.

Robotic systems of the future may still require some rigid components based on conventional engineering materials for structural stability and conventional components such as microprocessors. A mismatch of stiffness at the interface between components causes stress concentrations, which can lead to mechanical failure of the connection; this issue is widely known in fields such as stretchable electronics, but general frameworks that allow bonding of various classes of hard materials and soft materials are not yet established, impeding practical applications. Different strategies have been developed to achieve robust and reliable interfacial adhesion, including chemical bonding, physical interaction (for example, through hydrogen bonds, connector polymers, or mechanical interlocking with porous hard materials), and functionally graded materials (which feature a gradual change in stiffness to avoid stress concentrations) (Fig. 1e(i),(ii))[36–39]. Despite these existing methods, realizing robust and reliable bonding between soft and hard materials is still challenging due to their dramatically different properties, particularly when the interface is subjected to millions of cycles of loading as required in many practical applications. For example, crazing is a phenomenon that leads to a network of small cracks at the interfaces of glassy polymers; its understanding is important for predicting crack nucleation, among other failure modes. As the adhesion strength of soft-to-hard polymer interfaces reaches levels of bond strength comparable to those of glassy polymers, thermal and mechanical cyclic loading might also cause crazing at these interfaces. Therefore, crazing management and reversal will become an important research target for advancing soft-to-hard interfaces.

When integrating a functional soft material into a robotic system we must not only strive for a strong, reliable mechanical connection, but we must also consider how these materials interact functionally with other components of a robot. Whereas conventional robotic components typically use electrical signals, many functional soft materials use other physical stimuli such as heat, light, chemicals or ions. Materials scientists must develop interfaces that efficiently link one type of physical stimulus with another. For example, we have developed an interface that allows transmission of high-voltage signals between electronic and ionic conductors without causing electrochemical reactions (Fig. 1e(iii))[40]. In particular, interfaces between multiple functional soft materials that do not rely on electrical signals for communication remain virtually unexplored to date. Interfacing is further complicated for cases when a single interface must transmit different types of signal simultaneously. Further, developing interfaces that reliably connect components that use different physical stimuli will require collaboration of materials scientists with experts from fields such as electrochemistry and optoelectronics, which already investigate interface phenomena on a fundamental level.

The inherent compliance of functional soft materials enhances the safety and

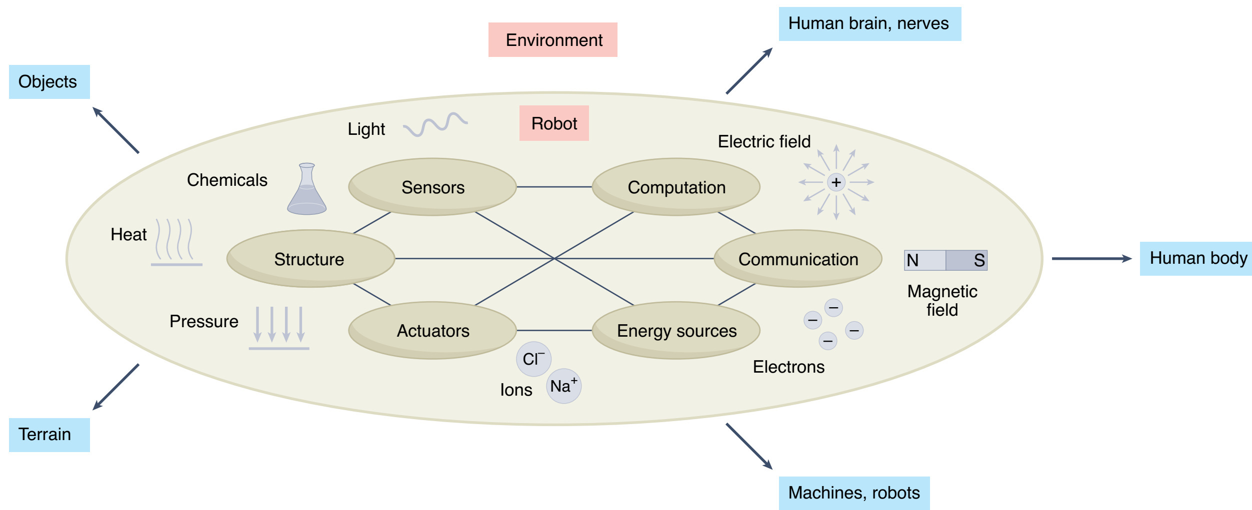

Fig. 3 | Interfaces between components inside a robot and between a robot and its environment. Even though effective and robust interfaces are crucial for creating high-performance robotic systems, materials scientists have largely neglected to develop such interfaces for functional soft materials. We must now develop new methods and principles to reliably connect components that have vastly different mechanical properties and function based on diverse physical stimuli such as light, heat, electric or magnetic fields. Additionally, materials scientists must develop interfaces that allow robots to safely and effectively interact with their environment.

comfort of robotic systems when interacting with the human body. In the field of wearable robots for assistance, augmentation and rehabilitation, for example, soft robotic exosuits[32] and gloves[31] based on flexible tendon-driven actuation or pneumatically driven artificial muscles are on the verge of commercialization. Further, there are many encouraging examples of implantable devices that are designed to interact with internal organs or tissues, such as a soft robotic heart sleeve that can support cardiac functions by mimicking the squeezing and twisting motion of the beating heart (Fig. 1e(iv))[33]. For such implantable robotic devices, however, having softness alone would not guarantee their safety. Instead, designing their interfaces to ensure mechanical and chemical compatibility with the interacting tissues is of critical importance to prevent or minimize potential tissue damage. Biological tissues possess extreme mechanical properties such as high mechanical strength, fracture and interfacial toughness, resilience, and fatigue resistance — most even combine several of these properties while still being soft[37]. While design principles for individual mechanical properties have been established, improving multiple properties at the same time is still practically challenging because they are often coupled with one another (for example, increasing stiffness of an elastomer typically reduces its stretchability). Learning design principles from biological counterparts may lead to orthogonally decoupled design strategies; this calls for a close collaboration among biologists, materials scientists and mechanicians.

Brain–machine interfaces will become essential for mind control of prostheses and wearable robots of the future. Even though the brain is one of our most delicate and vulnerable organs, traditional brain implants and neural probes are mostly based on rigid materials. The mismatch in mechanical and chemical properties between the implanted probes and the nervous tissues can lead to chronic tissue damage and unwanted inflammatory responses[34]. Soft bioelectronics can offer a safer means of interfacing with the nervous system. For example, we have introduced soft and flexible neural probes based on hydrogel-coated multifunctional fibres (Fig. 1e(v))[34] as well as hydrogels with different mechanisms of charge conduction (hydrogels with dissolved ions or conductive fillers, or hydrogels of conducting polymers)[35], which have shown the capability of sensing and triggering neural activities for several months while offering stable and effective bioelectronic interfaces. Despite the demonstrated potential, there are still a number of challenges that must be addressed to advance soft neuronal interfaces beyond proof-of-concept demonstrations, such as mechanical failure of and the foreign body response to the bioelectronic devices. These problems also include the development of a better understanding of the long-term interaction of bioelectronic devices with nervous tissue in order to ensure a level of safety, efficacy and reliability that will allow soft neural probes to be permanently connected to the human body. Addressing these problems will certainly require joint efforts from industry, academia and clinics.

With the advances of functional soft materials, the boundaries between robotics and materials science have become less apparent. Over the past decade, we have seen many exciting advances in materials science that have enabled new robotics applications that would have been considered infeasible or even unthinkable before. While many of the unique abilities of robotic systems based on functional soft materials are considered transformational, there remain numerous challenges ahead for these systems to be widely adopted as commercial products and to be recognized as powerful tools in practical applications. Therefore, we believe that further collaborations with industry (for example, through start-ups) is crucial; our experience has shown that research and development in companies focused on solving practical problems often reveals issues that would remain unnoticed in an academic setting, and that these issues can lead to highly interesting new fundamental research questions for academic research. As discussed in this Comment, research must now focus on realizing the predicted performance of the most promising technologies and on creating effective and robust interfaces to integrate individual components into highly functional soft robotic systems. Given the nature of these challenges, we expect that they can only be solved by highly interdisciplinary teams of researchers. Overall, we expect that innovation in functional soft materials will play a central role in shaping the future of robotics. ❐

Philipp Rothemund[1], Yoonho Kim[2], Ronald H. Heisser[3], Xuanhe Zhao[2,4], Robert F. Shepherd[3] and Christoph Keplinger[1,5,6] ✉

[1]*Robotic Materials Department, Max Planck Institute for Intelligent Systems, Stuttgart, Germany.* [2]*Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA, USA.* [3]*Sibley School of Mechanical and Aerospace Engineering, Cornell University, Ithaca, NY, USA.* [4]*Department of Civil and Environmental Engineering, Massachusetts Institute of Technology, Cambridge, MA, USA.* [5]*Paul M. Rady Department of Mechanical Engineering, University of Colorado, Boulder, CO, USA.* [6]*Materials Science and Engineering Program, University of Colorado, Boulder, CO, USA.*

✉*e-mail: ck@is.mpg.de*

Published online: 23 November 2021
https://doi.org/10.1038/s41563-021-01158-1

References

1. Haines, C. S. et al. *Science* **343**, 868–872 (2014).
2. Hu, W., Lum, G. Z., Mastrangeli, M. & Sitti, M. *Nature* **554**, 81–85 (2018).
3. Ilievski, F., Mazzeo, A. D., Shepherd, R. F., Chen, X. & Whitesides, G. M. *Angew. Chem. Int. Ed.* **50**, 1890–1895 (2011).
4. Shintake, J., Rosset, S., Schubert, B., Floreano, D. & Shea, H. *Adv. Mater.* **28**, 231–238 (2016).
5. Rothemund, P. et al. *Sci. Robot.* **3**, eaar7986 (2018).
6. Wehner, M. et al. *Nature* **536**, 451–455 (2016).
7. Vantomme, G. et al. *Nat. Mater.* https://doi.org/10.1038/s41563-021-00931-6 (2021).
8. Kim, Y., Parada, G. A., Liu, S. & Zhao, X. *Sci. Robot.* **4**, eaax7329 (2019).
9. Hawkes, E. W., Majidi, C. & Tolley, M. T. *Sci. Robot.* **6**, eabg6049 (2021).
10. Acome, E. et al. *Science* **359**, 61–65 (2018).
11. Kim, Y., Yuk, H., Zhao, R., Chester, S. A. & Zhao, X. *Nature* **558**, 274–279 (2018).
12. Ohm, C., Brehmer, M. & Zentel, R. *Adv. Mater.* **22**, 3366–3387 (2010).
13. Kellaris, N., Gopaluni Venkata, V., Smith, G. M., Mitchell, S. K. & Keplinger, C. *Sci. Robot.* **3**, eaar3276 (2018).
14. Rothemund, P., Kellaris, N., Mitchell, S. K., Acome, E. & Keplinger, C. *Adv. Mater.* **33**, 2003375 (2021).
15. Kellaris, N., Venkata, V. G., Rothemund, P. & Keplinger, C. *Extrem. Mech. Lett.* **29**, 100449 (2019).
16. Xu, T., Zhang, J., Salehizadeh, M., Onaizah, O. & Diller, E. *Sci. Robot.* **4**, eaav4494 (2019).
17. Zhang, J. et al. *Sci. Robot.* **6**, eabf0112 (2021).
18. Xu, P. A. et al. *Sci. Robot.* **4**, eaaw6304 (2019).
19. Kramer, R. K., Majidi, C. & Wood, R. J. In *2011 IEEE International Conference on Robotics and Automation* 1103–1107 https://doi.org/10.1109/ICRA.2011.5980082 (IEEE, 2011).
20. Lipomi, D. J. et al. *Nat. Nanotechnol.* **6**, 788–792 (2011).
21. Sun, J.-Y., Keplinger, C., Whitesides, G. M. & Suo, Z. *Adv. Mater.* **26**, 7608–7614 (2014).
22. Kaltenbrunner, M. et al. *Nature* **499**, 458–463 (2013).
23. Kim, D.-H. et al. *Science* **333**, 838–843 (2011).
24. Van Meerbeek, I. M., De Sa, C. M. & Shepherd, R. F. *Sci. Robot.* **3**, eaau2489 (2018).
25. Bai, H. et al. *Science* **370**, 848–852 (2020).
26. Aubin, C. A. et al. *Nature* **571**, 51–57 (2019).
27. Drotman, D., Jadhav, S., Sharp, D., Chan, C. & Tolley, M. T. *Sci. Robot.* **6**, eaay2627 (2021).
28. Aubin, C. et al. *Nature* (in the press).
29. Kim, Y., van den Berg, J. & Crosby, A. J. *Nat. Mater.* https://doi.org/10.1038/s41563-020-00909-w (2021).
30. Peng, Y. et al. *Nat. Mater.* https://doi.org/10.1038/s41563-021-00990-9 (2021).
31. Kang, B. B., Choi, H., Lee, H. & Cho, K.-J. *Soft Robot.* **6**, 214–227 (2019).
32. Kim, J. et al. *Science* **365**, 668–672 (2019).
33. Roche, E. T. et al. *Sci. Transl. Med.* **9**, eaaf3925 (2017).
34. Park, S. et al. *Nat. Commun.* **12**, 3435 (2021).
35. Yuk, H., Lu, B. & Zhao, X. *Chem. Soc. Rev.* **48**, 1642–1667 (2019).
36. Yang, J., Bai, R., Chen, B. & Suo, Z. *Adv. Funct. Mater.* **30**, 1901693 (2020).
37. Zhao, X. et al. *Chem. Rev.* **121**, 4309–4372 (2021).
38. Yuk, H., Zhang, T., Lin, S., Parada, G. A. & Zhao, X. *Nat. Mater.* **15**, 190–196 (2016).
39. Bartlett, N. W. et al. *Science* **349**, 161–165 (2015).
40. Keplinger, C. et al. *Science* **341**, 984–987 (2013).

Acknowledgements

P.R. and C.K. acknowledge funding by the Max Planck Society, Germany. Y.K. acknowledges funding through scholarships from ILJU Academy and Culture Foundation and MIT School of Engineering MathWorks Fellowship. X.Z. acknowledges funding from the National Institutes of Health (no. 1R01HL153857-01) and the National Science Foundation (no. EFRI-1935291).

Author contributions

C.K. developed the concept of the article. P.R. and C.K. led and coordinated the writing of the article. All authors contributed to the content and writing of the article.

Competing interests

P.R. and C.K. are listed as inventors of patents that cover fundamentals and basic designs of HASEL actuators as well as methods of fabrication. Y.K. and X.Z. are listed as inventors of patents that cover fundamental principles and fabrication techniques for 3D-printed magnetic soft actuators and magnetically steerable soft continuum robots. X.Z. is a co-founder of SanaHeal Inc., a start-up company commercializing bioadhesives. R.F.S. is listed as an inventor for patents regarding stretchable lightguide-based optical sensing platforms, and is a co-founder of Organic Robotics Corporation, which licenses these patents. C.K. is a co-founder of Artimus Robotics, a start-up company commercializing HASEL actuators.

Additional information

Peer review information *Nature Materials* thanks the anonymous reviewers for their contribution to the peer review of this work.