The painstaking pace of bioelectronic interfaces

Increased power efficiency, standardization and functionality enhance the biomedical prospects of electronic devices for interfacing the body.

Pacemakers, deep brain stimulation and powered limb prostheses have improved the quality of life of individuals with abnormal heart rhythms, neurological conditions such as Parkinson's disease, and amputated limbs. Today, computerized electronics capturing data from the body augment our physical and mental qualities: smartphones, smartwatches and other commercial wearables can alert us to a higher-than-usual heart rate, to low oxygen saturation in the blood and to dangerous exposures to high decibels, give us a long-term view of our sleep habits, and silently guide us through walks in unknown neighbourhoods (via touch sensations on our wrists, for example). Yet such external devices with continuous sensing and on-device computation have less stringent operational and safety requirements than electronic devices that need to be implanted to treat disease. A smartwatch that has run out of battery is a nuisance; a neural implant gone wrong can cause trauma.

In this respect, the recent progress update from Neuralink — one of Elon Musk's endeavours — exemplified the company's sheer ambition as well as the need for caution and grounded expectations when the success of the technologies being developed will largely depend on navigating crudely understood neurobiology and neuroimmunology, rather than on cleverly mastered integrated electronics and fabrication processes. In the highly publicized event, the company showed real-time wireless readings of neuronal activity in the somatosensory cortex of a pig while it sniffed around — an undertaking commensurate to what neuroscientists had achieved decades ago — and then claimed to eventually be able to use their high-throughput electrode-array and automated electrode-implanting technologies to allow individuals with paraplegia to walk, healthy people to intuitively play computer games, and scientists to determine the nature of consciousness. Neuralink's deep pockets and high public profile may attract welcome attention (and funding) for research in neuroelectronics. But the company's purposeful downplay of the challenges involved in achieving electronic brain implants that are safe, robust and functional for chronic use could jeopardize the wider credibility of the experts who painstakingly make progress while conveying realistic expectations.

This issue includes six examples of such progress towards making bioelectronic interfaces less power-hungry, easier to prototype and more functional.

Lessening the power requirements of bioelectronic interfaces without compromising their performance can facilitate their miniaturization and integration (by way of smaller batteries and electronic components). Lower power needs can also aid wireless data transfer and data throughput, and increase the devices' functionality (for example, via more sensing or actuation elements, or a larger number of electrodes). In brain–computer interfaces, reductions in power consumption can be achieved by recording brain signals at a lower fidelity. In fact, for intracortical electrode arrays, Cynthia Chestek and colleagues report that, in monkeys, the closed-loop and open-loop decoding of one-dimensional and two-dimensional motor tasks, respectively, can be done at lower power than currently achieved (typically by measuring the rates of threshold-crossing events; that is, of voltage potentials exceeding the threshold set for each electrode) by recording specifically from a narrower band (300–1,000 Hz) of neural spiking activity that contains accurate spike information at low signal-to-noise ratios. For the same type of electrode arrays, Nir Even-Chen and colleagues studied trade-offs between signal quality and decoder performance by using pre-recorded data from monkeys and a human participant. They found that bandpass-filter parameters could be relaxed without a loss of performance and that circuit-level opportunities (in specifications of the amplifier, analogue-to-digital converter and wireless-transmitter circuits) and system-level opportunities (carrying out data dimensionality reduction on chip, in particular) can also lead to power-saving efficiencies.

Standardized systems that facilitate performance comparisons and validation as well as easier prototyping can uncover engineering bottlenecks and spearhead innovation. Elliott Rouse and co-authors describe the design and characterization of an integrated robotic knee–ankle prosthesis (pictured), and its performance in individuals walking on level ground and up and down ramps and stairs. And in the website www.opensourceleg.com, the authors provide step-by-step guides (for both the hardware and the control systems) and video demonstrations of how to build and test the open-source prosthetic leg. In another Article, Pavel Musienko and co-authors show that the robotic ink-jet deposition of conductive inks, the extrusion of silicone pastes and the use of cold-air plasma to activate electrode surfaces can be leveraged to rapidly prototype neural electrode arrays customized for specific anatomical sites (such as the cortex, the spinal cord, the sciatic nerve and striated muscle) and applications, by recording and stimulating activity in a range of electrogenic tissue in zebrafish, rats and cats.

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Progress towards increased functionality often involves solving specific application needs by adapting and building upon existing technology. John Rogers and colleagues integrated conformable soft electronics with endocardial balloon catheters to enhance their diagnostic and therapeutic functionality. The electronics can be generated in multiple layered configurations to map temperature, pressure and electrical signals at high density (from about 160 sensor or actuator elements per square centimetre) and with fast switching and multiplexing possibilities, and to enable programmable electrical stimulation for radiofrequency ablation and electroporation, as the researchers show in rabbit and human hearts ex vivo. Another example is that provided by Canan Dagdeviren and colleagues, who integrated soft piezoelectric thin films that conform to the curvature of the face, multiphysics modelling and three-dimensional digital image correlation to detect and classify facial movements in real time, as they show for a few motions (open mouth, smiling and pursed lips) performed by volunteers, including individuals with amyotrophic lateral sclerosis. The technology, currently at the proof-of-concept level, is aimed at facilitating non-verbal communication in people who cannot speak.

Neuralink's dreams of merging artificial intelligence with the human brain will require huge leaps in neurobiology, such as identifying collective neural activity underlying specific cognitive tasks, understanding the mechanisms of neuroplasticity, efficiently decoding stable signals and designing implants that reduce the foreign-body effect. In the meantime, engineers will continue to make headway, mostly through careful research and development, and seldom by way of truly original inventions or fundamental breakthroughs. Although less celebrated, compounding improvements can end up amounting to a giant stride. ❐

https://doi.org/10.1038/s41551-020-00639-z