The future of brain–computer interfaces in medicine

Growing interest in non-invasive brain–computer interfaces, rather than implants, might improve accessibility for patients, but resolution needs to be improved.

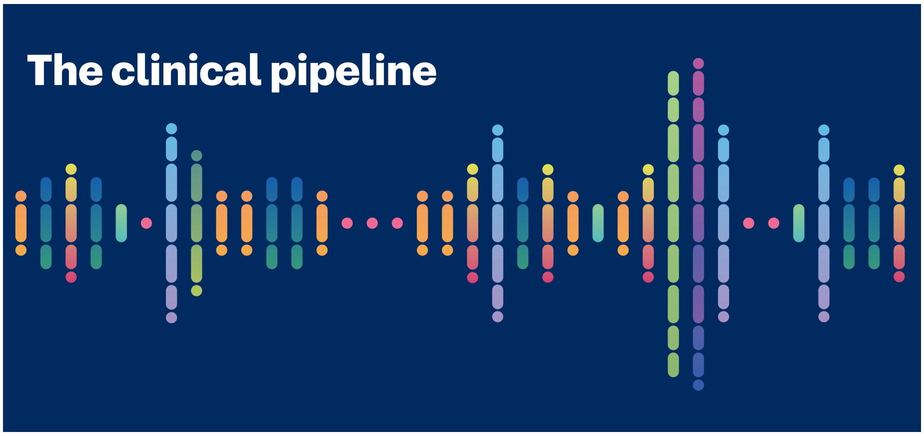
By Paul Webster

There is a worldwide race for marketable medical devices that harness brain–computer interfaces (BCIs). So far, attention has largely focused on sensors implanted in the brain and connected to computers, but such implants are medically risky and expensive. This means brain implants will probably only ever reach niche populations of wealthy patients, says José del R. Millán, co-director of the Cellular to Clinically Applied Rehabilitation Research and Engineering program at the University of Texas at Austin.

Partly because of these concerns, research is now intensifying on non-invasive BCI devices, Millán says. These use headsets and a growing range of unobtrusive electroencephalographic sensors attached to the outside of patients' skulls. "Ultimately, we can help far larger patient populations with non-invasive devices than we can with invasive devices," he says.

To prove his point, Millán slips on a pair of thick-framed spectacles during an interview. "Imagine if these contained microsensors capable of reading and transmitting my brain signals to a computer," he proposes. "Obviously, that would be a lot simpler than surgically implanting sensors in my brain."

Millán conceptualizes non-invasive BCI as an 'exoskeleton' for the brain that feeds information to a computer and then back to the user's brain. The technology is constrained by the far lower resolution of brain signals from electroencephalograms than is currently delivered by implanted sensors, he says, which could "be a big limitation for non-invasive BCI." However, this low resolution could be boosted by as-yet-untested sensor technologies, such as ultrasound and microwave, coupled with artificial intelligence-based brain signal analyses, which could allow external robotic devices such as prosthetic limbs or speech simulators to infer what the patient is thinking in a stable, continuous bidirectional manner. "I think that, given time and funding, we can develop very powerful systems in which the BCI exoskeleton almost becomes part of the brain," says Millán. "That's where I believe the field should go."



In a study published in February 2024, Millán and colleagues showed that inexperienced users could immediately operate a non-invasive BCI device, avoiding the need for the usual calibration data required to build a decoder. His stable, non-invasive BCI model relies on "a subject-independent decoder built on data of one single expert subject," says Millán. This renders calibration unnecessary because the decoder is, in a sense, bespoke tailored for the patient.

Cuntai Guan, director of the Centre for Brain-Computing Research at Nanyang Technological University in Singapore, agrees with Millán that non-invasive brain sensors show growing promise, especially for helping patients recover from brain damage or illnesses. "The most promising area is in helping patients recover their upper body mobility," he explains. In a 2021 paper, Guan described an approach to BCI electroencephalography in which a deep learning neural network is used to decode hand motor imagery. "That was a big jump," he says, "and it was driven by deep learning." However, as with many other researchers, Guan now seeks richer streams of brain data and more-sophisticated pretrained models.

An unresolved conundrum for BCI is how to achieve stable continuous communication, says Mariska Vansteensel, assistant professor of pediatric neuroscience at University Medical Center Utrecht, in the Netherlands. At present, constant computer recalibrations and neural decoder retraining are needed to cope with changes in the neural activities of patients. These brain signal instabilities arise from the patient's mental condition, which can affected by fatigue, time of day and the progression of brain diseases that may be present, as well as other factors. "These questions really need to be answered," says Vansteensel, who is also president of the Brain-Computer Interface Society.

To help find these answers, Vansteensel believes that BCI research should track patients outside laboratory settings, such as when they are at home and going about their lives, to provide researchers with rich brain signal data streams. Gernot Müller-Putz, head of the Laboratory of Brain-Computer Interfaces at Graz University of Technology, in Graz, Austria, is also pushing to bring BCI home. He works with patients with motor neuron disorders, trauma and stroke, who risk losing all muscle control to locked-in syndrome, where all forms of communication cease.

Within a study now undergoing an ethics review, Müller-Putz aims to develop a high-resolution and sustainable communication device for patients that combines hardware and software solutions (including artificial intelligence) to free patients with locked-in syndrome from their isolation. "We want to

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understand patients' brain signals in real-life settings, and to see how the device we're testing works in the real world," he says. To do this, he plans to send patients home with implanted sensor devices and slow but functional communication, and then gather data from them day and night.

Taking patients with brain implants out of the lab and into their homes could pose ethical challenges. Bioethicist Marcello Ienca at École Polytechnique Fédérale de Lausanne considers some BCI research to exist in what he calls an ethical grey zone in which research guidelines may require further refinement as research modalities evolve. "We need these BCI technologies at a time when it is estimated that one in three people alive today will develop neurological issues," says Ienca, "but I think specific governance and ethical research rules for the BCI field are now needed." Ienca is especially concerned about bidirectional BCI approaches whereby computers feed signals back into the brains of patients rather than simply receiving signals from patients.

There is an upswing in global BCI research from groups in the United States, Europe and Asia, says Dan Rubin, a critical care neurologist at Massachusetts General Hospital in Boston, which means that new BCI-based medical tools may soon "make their way to patients' bedsides," he says.

Rubin was involved in a pair of what he calls "moonlanding papers" published in *Nature* by the BrainGate group in 2021 and 2023. The latter of these two studies described a neuroprosthesis that decoded attempted speech by a patient at a rate of 62 words per minute, which, according to the researchers, approaches the speed of natural conversation. The research by BrainGate could restore communication for people with paralysis who can no longer speak, although the study authors cautioned that, as with other BCIs, recalibration is regularly needed to account for changes in neural activity.

Variability in brain anatomy is also a potential concern, warned the researchers, some of whom have collaborated in high-profile commercial BCI initiatives, including the Neuralink venture by Elon Musk, which published a video on X showing a patient who was paralyzed move chess pieces on a computer screen. However, at the time of writing, these findings have not been peer reviewed or published on a preprint.

BCIs might be especially promising for patients with neurodegenerative diseases, such as amyotrophic lateral sclerosis, says Rubin, who spoke with *Nature Medicine* during a pause from his work in the intensive care unit at Massachusetts General Hospital. The day may soon come, he forecasts, when the fruits of BCI experimentation "will successfully be transferred to patients via private companies."

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