NEWS & BUZZ

Applications over the horizon — Advancements and challenges in brain-computer interfaces

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Brain-computer interface (BCI) has emerged as a cutting-edge technology that aims to establish a direct communication pathway between human brain and external devices.[1] One of the main purposes of BCIs is to enable individuals to control external devices or interact with virtual environment using their brain activities. By interpreting neural signals and translating them into commands, BCIs have the potential to restore mobility to paralyzed individuals, enhance human-computer interaction, and unlock new possibilities in many fields such as medicine, gaming, and communication. In the past few years, notable progress has been made in this field. On January 29, 2024, two significant breakthroughs were reported: one was "Telepathy" stemming from Neuralink, a company founded by Elon Musk in the United States, and the other was BCI NEO (Neural Electronic Opportunity) device from a joint team at Tsinghua University and Xuanwu Hospital, China. Both teams recently completed the first wireless & implantable BCI clinical human trials, achieving noteworthy milestones that have attracted considerable market attention and reinvigorated research enthusiasm on BCI.

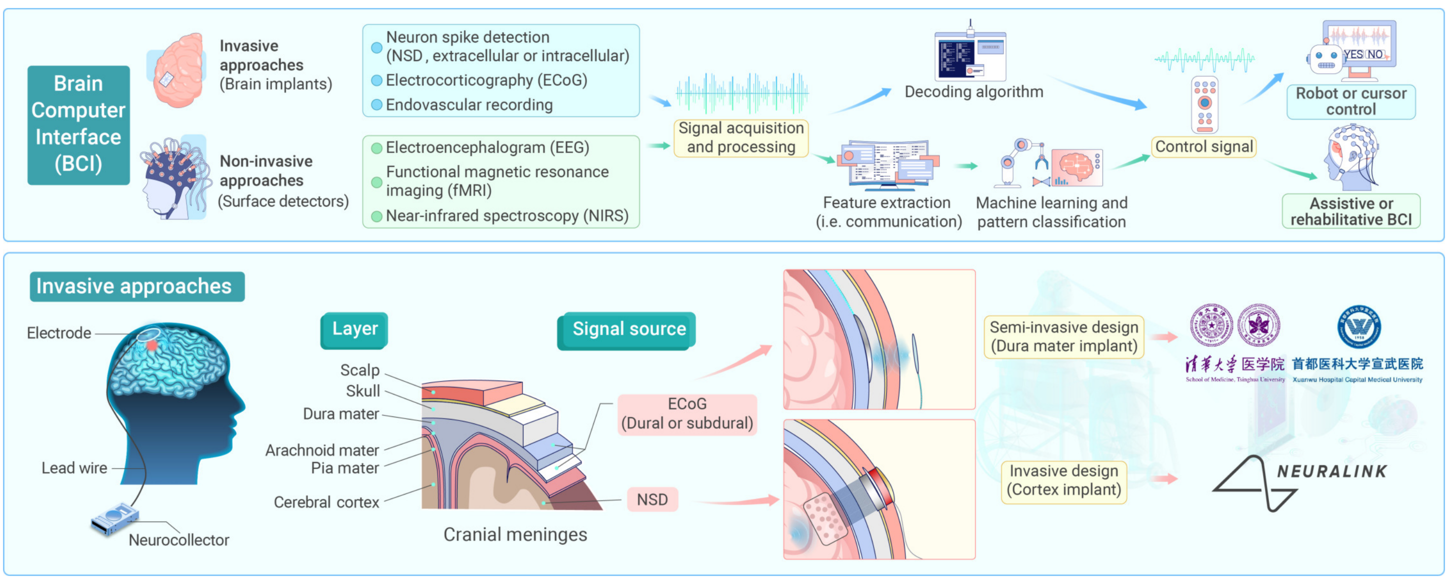

Figure 1. Exciting advancements in BCI Upper is the illustrative schematic of BCIs, including methodology and technical approaches. The recently reported BCIs from the Chinese and US research teams both employed invasive approaches, with NEO using a semi-invasive design and Telepathy using an invasive design.

A BCI system comprises the brain or central nervous system (CNS), brain signal acquisition, neural feedback, signal processing and decoding, control interface, and peripheral devices (upper in Figure 1). The user' CNS is the most complex, active, and highly adaptive subsystem that is indispensable to the BCI system. Thus, the design and evaluation of BCI systems need to prioritize users and ergonomics. Brain signal acquisition is another crucial component of BCI systems and usually one of the practical bottlenecks; acquiring high-quality brain signals is paramount. Nowadays, brain activities can be recorded using a variety of techniques, such as neuron spike detection (NSD, extracellular or intracellular), electrocorticography (ECoG), electroencephalogram (EEG), magnetoencephalography (MEG), positron emission tomography (PET), functional magnetic resonance imaging (fMRI), and functional near-infrared spectroscopy (fNIRS).[2] Among them, MEG, PET, and fMRI are technologically demanding, expensive, and not portable, limiting their widespread applications in BCI. On the other hand, PET, fMRI, and fNIRS rely on detection of brain metabolism, offering high spatial but low temporal resolutions, thus are not well suited for rapid brain-machine interaction at current technological levels. EEG can noninvasively record signals from the scalp, ensuring safety. However, its spatial resolution and signal-to-noise ratio are not better than invasive ECoG and NSD, which also has broader frequency bands and less susceptibility to artifacts. Comparably, they are popular as the primary option to implanted BCI currently. Recent progresses made at Telepathy and NEO were based on the acquisition of extracellular NSD and ECoG signals, respectively.

Neuralink, founded by Elon Musk in 2016, has made progress toward a flexible, scalable BCI. They aim to treat memory loss, cervical and spinal cord injuries, and other neurological disorders, and to help paralyzed people regain the ability to communicate with the outside world or even to walk. In their first reported BCI device, they demonstrated rapid implantation of 96 polymer threads (each with 32 electrodes), yielding a total of 3,072 electrodes to record neuronal electric signals. They also developed miniaturized custom electronics that allow researchers to stream full broadband electrophysiology data simultaneously from all these electrodes. Moreover, the system was packaged for long-term implantation and customed online spike-detection software was developed to detect action potentials with low latency. Combining all these features, the system was the first prototype toward an wireless human brain-machine interface.[3] In May 2022, the Neuralink received approval from the Food and Drug Administration (FDA) of the United States to launch human clinical trials of brain implantable devices. In September that year, they began recruiting volunteers for the clinical trial. On

January 29, 2023, Musk announced online that Neuralink had performed the first human transplantation of a BCI device and that the transplant recipient was recovering well. Twenty days after implantation, the volunteer showed no adverse neurological effects and could control mouse movement on the screen by thinking. The device was implanted into the cerebral cortex of the patient, who managed to control cell phones or computers to express thoughts via neuron spike signals. The most recent progress from the company is Telepathy, which, however, requires invasive craniotomy (Figure 1 "Cortex implant"). The advantages are evident: it can achieve very sensitive readout of neural representations, necessitating the recording of single action potentials from neurons in distributed, functionally linked ensembles. However, concerns still revolve around user safety and the limited long-term usability of invasive schemes.

Differently, a joint research team from Tsinghua University and Xuanwu Hospital (China) has adopted an alternative BCI scheme that is semi-invasive. This team led by Prof. Bo Hong from The School of Medicine in Tsinghua University has worked on the principles, algorithms, and clinical translation of BCIs since late 2000s. Their research focuses on developing innovative approaches to improve the accuracy, reliability, and longevity of neural interfaces. In 2022, this team achieved an equivalent information transfer rate of 62 bits/min in the BCI speller with epilepsy patients.[4] On October 24, 2023, at Xuanwu Hospital in Beijing, a NEO device was successfully implanted into the brain of a patient who had been quadriplegic for 14 years due to complete spinal cord injury. Ten days post-surgery, the patient was discharged from hospital and returned home. After three months of home-based rehabilitation training, the patient can now drive the pneumatic glove through ECoG signal to realize brain-controlled functions like drinking water, and the accuracy of grasping decoding reaches more than 90%. The patient's ASIA scores of spinalcordiniure and sensory evoked potentials response have been significantly improved. Compared with Telepathy, the NEO has higher safety and more suitable for long-term use due to the adoption of a wireless minimally invasive design, where the intracorporeal module is buried in the skull and the electrodes are covered with dura mater (a protective membrane between the skull and the brain cortex, safeguarding neural tissue), without damaging the brain cells (Figure 1 "Dura mater implant"). The BCI processor is only the size of two coins. Through near-field wireless power supply and communication, the intracorporeal module is powered from outside the scalp and the neural signals are received and transmitted to a computer or cell phone, where decoding algorithms are employed to finalize the signal communication. Such a setting allows the patient to use the machine for a long term without needs for internal batteries.

Despite these exciting achievements, critical challenges exist for BCI.[5] First is the long-term stability and reliability of neural interfaces, as they can degrade or cause tissue damage over time. Researchers are actively exploring materials and designs that can enhance biocompatibility and longevity. Another challenge is the decoding of complex neural signals to achieve precise and intuitive control of devices. Human brain produces intricate patterns of activity. Accurate interpretation of these signals remains a significant scientific and engineering undertaking. Moreover, ethical considerations surrounding privacy, data security, and informed consent need to be carefully addressed as BCIs advance. Ensuring the responsible and ethical implementation of this technology is crucial to protect individuals' rights and build public trust.

Nonetheless, these recent advancements in developing advanced neural interfaces, decoding algorithms, and real-time brain control of devices showcase the transformative potential of BCIs and have considerably propelled forward the field. Ongoing research and collaboration hold promise to overcome existing obstacles and unlock the full potential of this groundbreaking technology, such as revolutionizing healthcare, gaming, communication, and various industries, ushering in a new era of human-machine interaction.

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DECLARATION OF INTERESTS

The authors declare no competing interests.