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Brain–Machine Interface: A Review of Current Technologies and Future Directions

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Abstract

Brain–machine interface (BMI) is a rapidly growing field that aims to establish direct communication between the brain and an external device. This technology has the potential to restore lost motor and sensory functions in people with neurological disorders or injuries. A brain–computer interface (BCI) is a technology that converts signals from the brain into instructions for computers or other gadgets. This innovation allows individuals to engage with their surroundings solely through their brain's actions, eliminating the necessity for peripheral nerves and muscles. The development of devices that enable impaired people to communicate with others, operate prosthetic limbs, or regulate their surroundings is the main objective of BCI research. Multimedia communication is a promising application area for brain–computer interfaces (BCIs). Currently, many aspects of BCI systems are being investigated to develop systems for assistive technology and multimedia communication. These research areas include assessing invasive and non-invasive technologies to measure brain activity, evaluating control signals (patterns of brain activity that can be used for communication), developing algorithms for translating brain signals into computer instructions, and creating new BCI applications. This paper aims to provide an overview of the current state of BMI technologies, as well as to explore their potential applications and future directions.

Keywords: Brain–machine interface, BMI, invasive, non-invasive, multimedia communication

INTRODUCTION

Few people could have imagined that efforts to create direct functional interfaces between brains and artificial objects, such as computers and robotic limbs, would have been so successful, and that in the process, a new field at the cutting edge of systems neuroscience would have been established. The field of brain–machine interfaces (BMIs), which was originally highly interdisciplinary, has progressed remarkably quickly since the initial experimental proof in 1999 that groups of neurons in the cerebral cortex could directly steer a robotic device. Since then, a steady stream of research papers has stoked both the scientific community's and the general public's intense interest in BMIs. This method has a great deal of potential for restoring motor behaviors in patients with severe disabilities, which is what has sparked people's interest in it. BMIs have primarily been thought of as a potential new therapy to regain motor control in severely injured individuals, particularly those dealing with life-threatening illnesses including amyotrophic lateral sclerosis (ALS), spinal cord damage, stroke, and cerebral palsy [1–4].

Invasive and non-invasive procedures are the two main categories for BMIs. While non-invasive

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techniques employ external devices to record brain activity, invasive techniques entail the direct insertion of electrodes into the brain. Invasive methods have the advantage of high-resolution and long-term stability, but they carry the risk of infection and other complications. Non-invasive methods are less risky, but they typically have lower resolution and shorter recording times. BMIs could be useful for amputees as this technology develops and the dangers of intrusive brain recordings go down. BMIs for restoring speech and locomotion are likely to develop in addition to the systems driving upper-limb prostheses [5].

BMI TOOLS

Three major factors seem to stand out from the present research when weighing the benefits and drawbacks of various recording instrument types:

1. Scale—the number of neurons that can be recorded at once.
2. Resolution—the level of detail in the data the tool receives; it might be either spatial or temporal.
3. Invasiveness—will surgery be necessary, and if so, how much?

fMRI

The brain imaging technique called functional magnetic resonance imaging (fMRI) has high scale and non-invasive invasiveness, but its spatial resolution is medium-low and its temporal resolution is very low. Although fMRI is a well-known recording method, it is not commonly employed for BMIs. It informs you of the internal processes taking on in the brain. Functional MRI utilizes magnetic resonance imaging, often referred to as MRI. The x-ray-based CAT scan was developed into the MRI in the 1970s. MRIs produce images of the body and brain using magnetic fields in place of X-rays, together with radio waves and other signals [6]. A related piece of equipment is used in fMRI (“functional” or “functional” MRI) (“functional” MRI), abbreviated fMRI (“functional” MRI) Where activity occurring can be inferred indirectly from blood flow. Results from fMRI are also three-dimensional since it can scan the entire brain. fMRI has a variety of medical applications, such as helping doctors determine whether specific brain regions are recovering well from a stroke Figure 1. It has also taught neuroscientists a great deal about which sections of the brain are responsible for which processes. Additionally, scans have the advantage of revealing information about what the entire brain is experiencing at any one moment while being completely non-invasive and safe. The resolution of fMRI represents a significant constraint. Like a computer screen, fMRI produces images made up of three-dimensional, cubic volume pixels known as “voxels.” As technology has improved, fMRI voxels have become smaller, leading to increased spatial resolution. However, even with high-resolution fMRI scans that divide the brain into nearly one million voxels, each voxel still contains tens of thousands of neurons. As a result, fMRI provides an average measurement of blood flow for groups of around 40,000 neurons, which is imprecise at the neuron scale. Moreover, fMRI exhibits a notably sluggish temporal resolution as it monitors blood circulation, which is both inexact and delayed by approximately one second – a considerable duration in the realm of neurons.

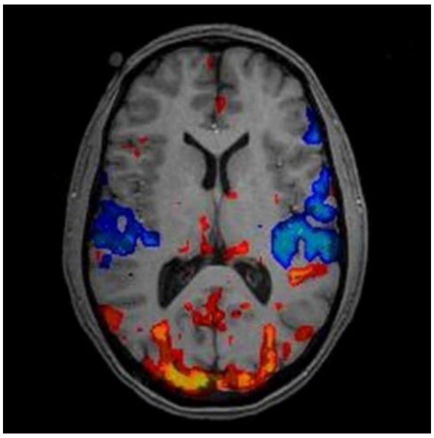

Figure 1. fMRI.

Electroencephalography

The recording method with high scale, but low spatial resolution and medium-high temporal resolution is electroencephalography (EEG). Electroencephalography, or EEG, has been used for almost a century and involves placing several electrodes on your head. It is one of the few completely non-invasive BMI measurement techniques available. EEGs record electrical activity Illustrating the results in this manner, [7] showcases distinct brain regions (Figure 2).

The status of a dose of anesthetic, for example, can be ascertained using EEG graphs, which can also reveal information about conditions like epilepsy and sleep patterns. Compared to fMRI, EEG offers better temporal resolution as it can capture electrical signals from the brain as they occur.

Yet, the effectiveness of EEG's spatial resolution is restricted by the skull's inadequate conduction of electrical signals. Each electrode on the scalp records a vector sum of the activity from many neurons, typically in the millions or billions, resulting in a wide average of brain activity. This lack of spatial precision is a significant drawback of EEG. Additionally, the skull can further blur the recorded signals, making it challenging to identify the precise location of neural activity. Despite these limitations, EEG remains a valuable tool for studying brain function, as it provides a non-invasive and relatively low-cost method of measuring brain activity in real-time.

Electrocorticography

Electrocorticography (ECoG) is a kind of invasive recording method that involves placing electrodes directly on the surface of the brain, underneath the skull. Therefore, it can be considered "kind of invasive". ECoG has a high scale and offers a relatively high temporal resolution compared to other invasive methods, but its spatial resolution is still limited. Like EEG, electrocorticography (ECoG) also uses surface electrodes but places them on the surface of the brain, under the skull. ECoG detects higher spatial (1 cm) and temporal resolution when the skull's interference is absent (5 milliseconds) Figure 3. ECoG electrodes have the option of being positioned either on top of or beneath the dura, as indicated by sources [8] and [9].

Local Field Potential (Microelectrodes)

The scale of local field potential (LFP) recording is relatively low, as it usually only captures activity from a small population of neurons in a specific region. However, LFPs offer a relatively high temporal resolution, allowing for the precise measurement of neuronal activity with a millisecond-level accuracy. The spatial resolution is medium-low, as the recorded signals are influenced by the surrounding neurons and glia. LFP is a measure of the electrical activity of the brain that is recorded from electrodes placed near or within the brain. It reflects the summed activity of many neurons in a specific area of the brain, rather than the activity of individual neurons. LFPs are typically measured using electrodes that are inserted into the brain (invasive electrodes) or placed on the surface of the skull (non-invasive electrodes). The LFP reflects a variety of neural processes, including synaptic activity, action potentials, and neural oscillations Figure 4. LFPs are typically in the range of millivolts (mV) and can be recorded using different techniques such as electroencephalography (EEG) or intracranial recordings. LFPs have been used in a variety of research areas, such as studying neural oscillations, neural coding, and the neural basis of behavior and cognition. LFPs can also be used in clinical settings, such as to monitor the brain activity of patients with epilepsy or Parkinson's disease. LFPs exhibit intricate signals containing various frequency ranges that correspond to distinct neural activities. Low-frequency LFPs (around 1–50 Hz) reflect synaptic activity and neural oscillations, while high-frequency LFPs (above 50 Hz) reflect the firing of individual neurons. In summary, LFP is a measure of the electrical activity of the brain that reflects the summed activity of many neurons in a specific area of the brain, rather than the activity of individual neurons. It can be recorded using different techniques and provides insight into different neural processes, such as synaptic activity, action potentials, and neural oscillations. A newer technology called the multielectrode array has emerged, which is like the LFP method but involves the simultaneous recording of around 100 LFP signals from a single cortical region. The multielectrode array has a distinct appearance resembling: [10]

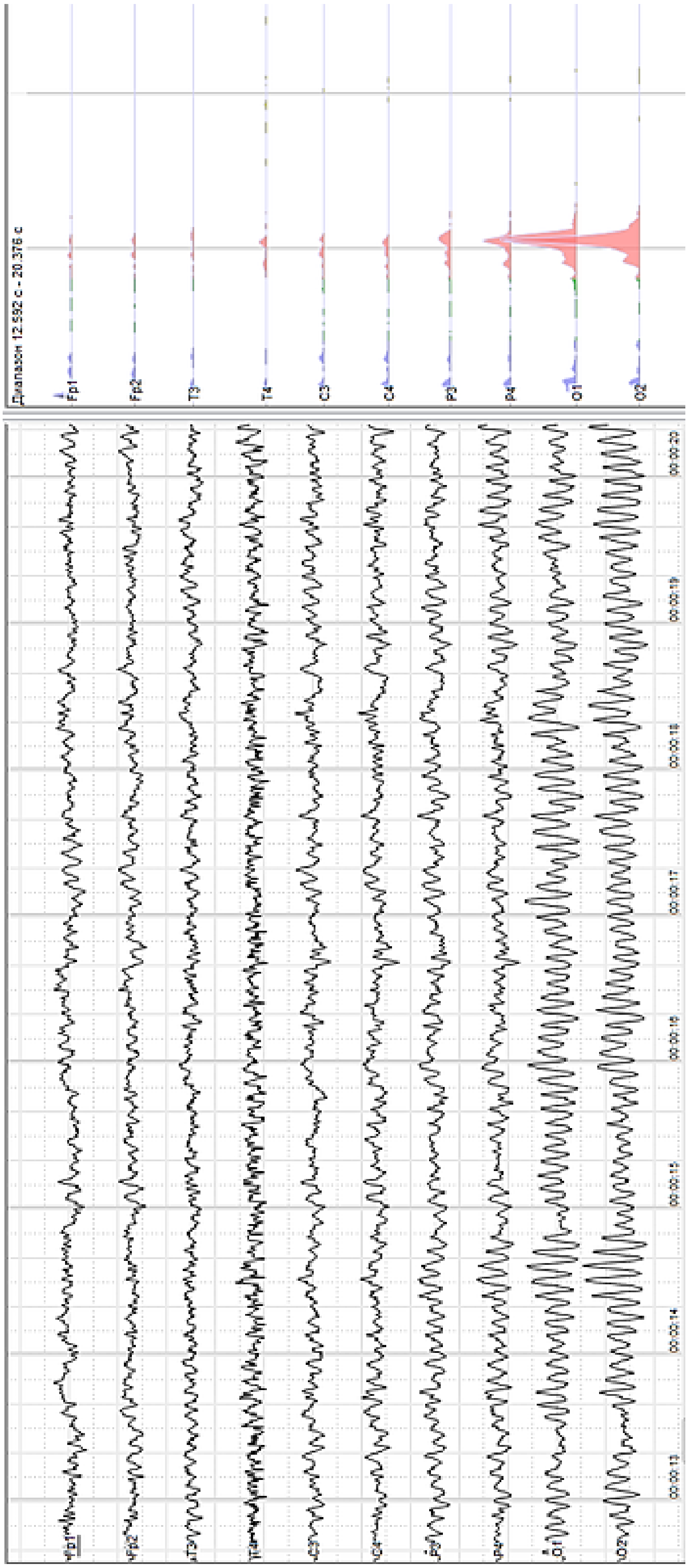
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Figure 2. EEG.

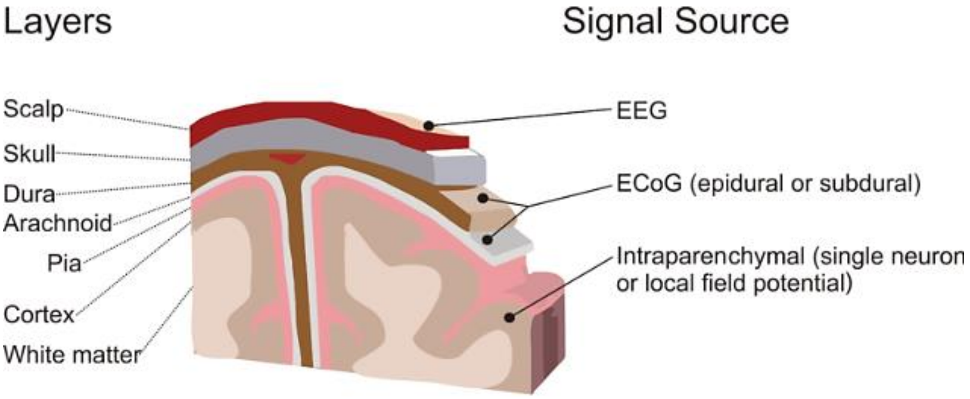


Figure 3. Electrocorticography.

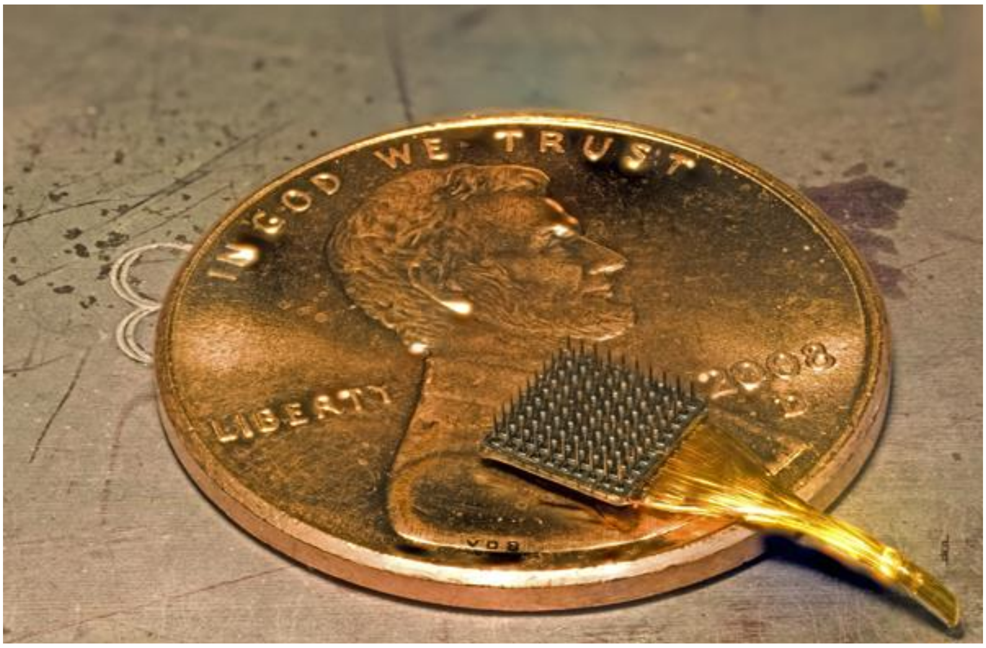


Figure 4. Microelectrodes.

Single-Unit Recording

The needle electrode is still used for single-unit recording, but the resistance is increased and the tip is made extremely sharp. This eliminates most of the noise, leaving the electrode picking up essentially nothing, until it comes within about 50 micrometers of a neuron, at which point the signal from that neuron is potent enough to pass through the electrode's thick wall of high resistance. This electrode may now eavesdrop on the private lives of a single neuron if it receives separate signals from that neuron and there is no background noise. the greatest resolution at the smallest scale.

EARLY BMI

Using the Motor Cortex as a Remote Control

The motor cortex is one of the more straightforward regions of the brain, even though all brain regions are complex. The body is well-mapped, with specific portions of the motor cortex controlling body parts. Moreover, the motor cortex is one of the primary brain regions responsible for our physical movements. Consequently, there's no requirement for the human brain to acquire new skills for employing the motor cortex as a remote control, as it is already fulfilling this role. The objective of brain–machine interfaces (BMIs) reliant on the motor cortex is to access this cortex, receive a command akin to one prompted by a remote control, and subsequently transmit the command to a machine, like how your hand functions. Just as nerves link your motor cortex to your hand, BMIs serve as a conduit connecting your motor cortex and a computer. One common form of interface allows individuals who are paralyzed from the neck down or have had limbs amputated to control a cursor on a screen using only their thoughts. Thanks to groundbreaking efforts by BrainGate, a man achieved the feat of controlling a video game solely through his thoughts [11]. In a simulation, a woman with quadriplegia piloted an F-35 fighter jet, and a monkey even steered a wheelchair using its mind [12, 13]. Nicolelis conducted an experiment that interconnected the motor cortex of a rat in Brazil with another rat's motor cortex in the United States, facilitated through the Internet [14].

Artificial Ears and Eyes

Categorizing brain–machine interfaces as methods to restore hearing to the deaf and vision to the blind appears more feasible due to several factors. Firstly, like the motor cortex, the sensory cortices are brain regions that are typically well-understood, largely due to their frequently well-mapped nature. Secondly, since the disability often arises from the point where hearing and vision connect to the brain, early applications can focus on these areas rather than the brain itself. Unlike research on the motor cortex, which primarily focuses on recording neurons to extract information from the brain, artificial senses operate in the opposite direction by stimulating neurons to receive information. The cochlear implant is a notable example of this approach, which has been developed in recent decades to address hearing loss. Within the ear, the cochlea plays a critical role in converting sound into neural signals. Thousands of tiny hairs within the cochlea vibrate in response to sound waves, generating electrical signals that stimulate the auditory nerve. A cochlear implant consists of a small computer with a microphone that sits on the ear and a wire that connects to a network of electrodes lining the cochlea Figure 5.

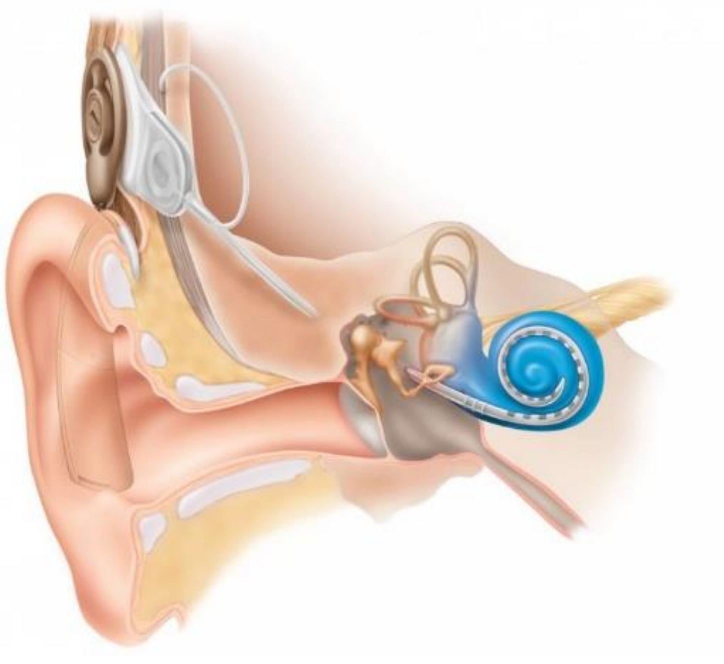


Figure 5. Ear Implant.

The development of retinal implants is also a significant breakthrough in the field of visual impairments.

In numerous instances, visual impairment results from retinal issues, and akin to cochlear implants for hearing (though indirectly), retinal implants Figure 6 can fulfill a similar role. These implants mimic regular ocular functions, relaying data to nerves through electrical signals. The Argus II implant, created by Second Sight, secured FDA approval as the first retinal implant, showcasing a more intricate interface compared to cochlear implants [15].

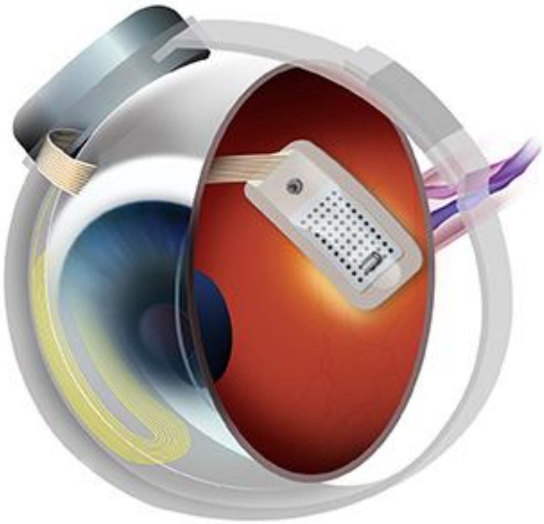


Figure 6. Eye Implant.

Deep Brain Stimulation

The pacemaker sends a small electrical current to the electrodes, which in turn modifies the activity of specific brain regions. Deep brain stimulation has been used to treat a variety of neurological disorders, including Parkinson's disease, essential tremor, and dystonia Figure 7. The exact mechanism by which deep brain stimulation works is not well-understood, but it is believed to involve the modulation of abnormal patterns of neural activity in specific brain regions. While deep brain stimulation is not a cure for these conditions, it can significantly improve symptoms and quality of life for many patients [16].

Figure 7. Deep brain stimulation.

When necessary, the electrodes can then provide a brief zap that has several beneficial effects. Like:

- Parkinson's patients' tremors can be lessened
- Reduce the severity of seizures
- Compose people with OCD

CURRENT INNOVATIONS

A team from the University of Illinois is developing a silk-based interface [17].

A thin bundle of silk Figure 8 can be wrapped up and rather painlessly introduced into the brain. In theory, it could disperse throughout the brain and conform to its shape as it contracts. There would be pliable silicon transistor arrays on the silk. A temporary tattoo-like electrode array Figure 9 was printed on Hong Yeo’s skin during his TEDx Talk, and experts believe this method might be applied to the brain [6].

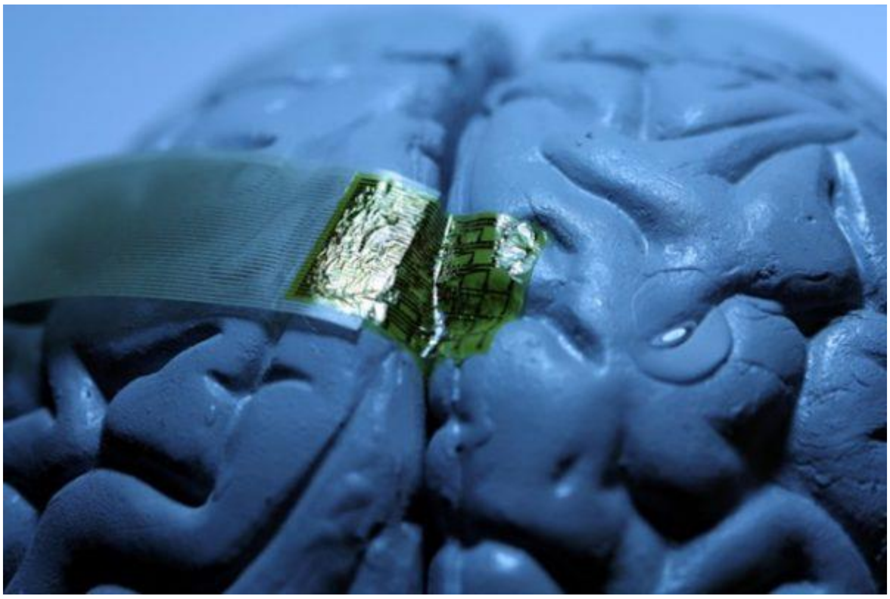


Figure 8. Silk interface.

Figure 9. Electrode tattoo.

Another team is working on a type of electrode-lined neural mesh Figures 10 and 11 that is nanoscale in size and can be injected into the brain using a syringe: [17]

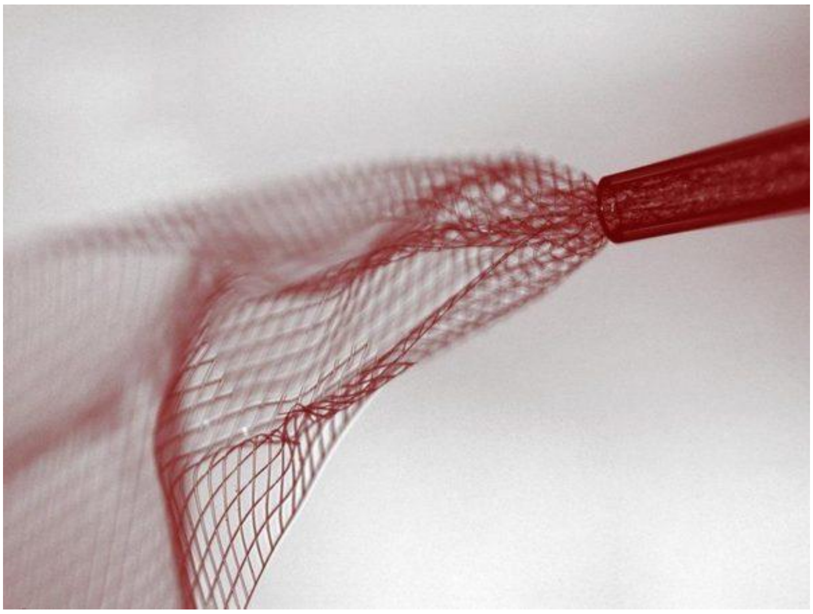
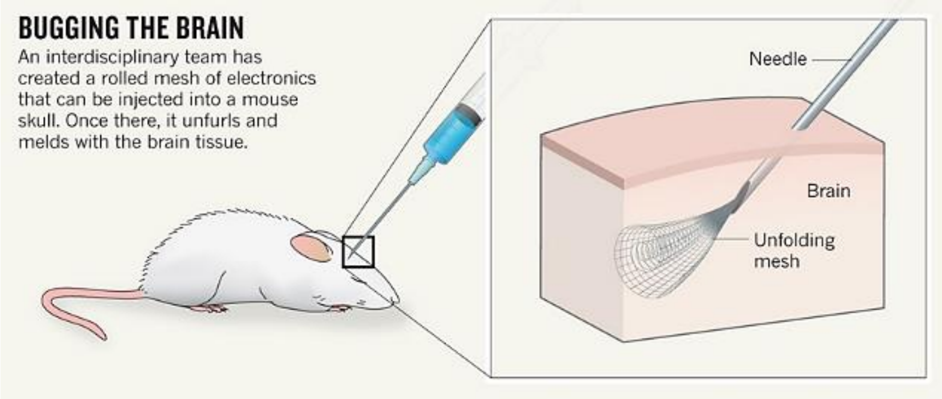


Figure 10. Neural mesh.



BUGGING THE BRAIN

An interdisciplinary team has created a rolled mesh of electronics that can be injected into a mouse skull. Once there, it unfurls and melds with the brain tissue.

Figure 11. Neural mesh demo.

FUTURE

BMI would drastically change how humans handle communication. “Communication” can refer to human-to-human / human-to-computer interactions. Human-to-computer connection is the focus of motor communication; this is an incredibly cool update to the old idea of using the motor cortex as a remote control.

The initial application of motor communication through brain–machine interfaces will focus on restoring motor function for people with disabilities, which is like other categories of potential brain interface technology. As advancements in this field continue to progress, likely, that the technology will also be used to develop applications for enhancing the motor abilities of non-disabled individuals.

The technology that allows a quadriplegic to control a bionic limb with their thoughts as a remote can also be utilized by anyone to manipulate objects designed for brain-operated control. Furthermore, this technology is anticipated to be widely employed in the construction of various items in the future. For example, opening your car’s door, setting the heater temperature, opening the fridge door, steering vehicles, playing piano, etc. all using only your mind.

Words are compressed approximations of uncompressed thoughts. Thoughts occur to humans at a rate much faster than they can speak. Thought communication would get rid of this lossy transmission and replace it with a way in which one directly communicates through thoughts with each other. It is difficult to fully grasp the experience of thinking in unison with another person since there has been no opportunity to do so. Our thoughts are conveyed internally, while communication with others is accomplished through symbolic means. This is the limit of our current understanding. Additionally, the idea of a collective consciousness is even more unusual to fathom. BMI could also feed one person with another's sensory information and make him/her feel those exact things. For example, one could go on a hike and the other could experience the same things he/ she might experience on a hike while sitting at home. The ability to read sensory input from the BMIs would also mean that one could record their dreams/memories and play them back.

CONCLUSION

BMI is a rapidly growing field with great potential to restore lost motor and sensory functions in people with neurological disorders or injuries. While the current state of the art in BMI technologies has shown promising results, there are still many challenges to be addressed, such as developing more robust and reliable implantable devices, improving the spatial and temporal resolution of non-invasive methods, and addressing ethical and social issues.

It is a swiftly advancing area of study that seeks to establish a direct link between the human brain and machines or computers. The goal of BMIs is to create a seamless connection between the brain and technology, allowing for direct control of devices and the ability to communicate with not only computers but also another person using only the power of thought. The potential of this technology to transform our interactions with machines and individuals is immense, potentially causing substantial advancements in fields like medicine, and prosthetics, as well as human-computer and interpersonal communication. However, there is still a lot of research that needs to be done to fully realize the potential of BMIs and overcome current challenges such as implant rejection, lack of precision, and long-term reliability.

REFERENCES

1. Lebedev MA, Nicolelis MA. Brain-machine interfaces: past, present and future. Trends Neurosci. 2006 Sep 1;29(9):536-46. doi: 10.1016/j.tins.2006.07.004.
2. Hortal E, Planelles D, Costa A, Iáñez E, Úbeda AJM, Azorín JM, et al. SVM-based Brain–Machine Interface for controlling a robot arm through four mental tasks. Neurocomputing. 2015 Mar 1;151:116-21. doi: 10.1016/j.neucom.2014.09.078.
3. Saha S, Mamun KA, Ahmed K, Mostafa R, Naik GR, Darvishi S, Khandoker AH, Baumert M. Progress in brain computer interface: challenges and opportunities. Front Syst Neurosci. 2021 Feb 25;15:578875. doi: 10.3389/fnsys.2021.578875.
4. Acerbi, A., and Mesoudi, A. (2015). If we are all cultural Darwinians what's the fuss about? Clarifying recent disagreements in the field of cultural evolution. Biol. Philos. 30, 481–503. doi: 10.1007/s10539-015-9490-2
5. Urban T. (20 Apr. 2017). Neuralink and the Brain's Magical Future. [online] Wait But Why. Available from: https://waitbutwhy.com/2017/04/neuralink.html
6. Templeton G. (2015, June 10). Amazing injectable neuro-mesh covers the brain, can control individual neurons. [online] ExtremeTech. Available from: https://www.extremetech.com/extreme/207848-injectable-neuro-mesh-covers-the-brain-can-control-individual-neurons
7. Friedrich EVC, McFarland DJ, Neuper C, Vaughan TM, Brunner P, Wolpaw JR. A scanning protocol for a sensorimotor rhythm-based brain-computer interface. Biol Psychol. 2009 Feb;80(2):169-75. doi: 10.1016/j.biopsycho.2008.08.004.
8. Brusch K. (2016). Brain Computer Interfaces for Full Body Movement and Embodiment. [online] Intelligent Robotics Seminar. Available from: https://tams.informatik.uni-hamburg.de/lehre/2016ws/seminar/ir/pdf/slides/KaiBrusch-BCI_for_Full_Body_Movement_and_Embodiment.pdf
9. Jonesblog. (2009, August 24). Bionic implants. [online] Utah.edu. Available from: https://prometheus.med.utah.edu/~bwjones/2009/08/bionic-implants/

10. Walter Farah. (2017, May 19). Brain Computer Interface. The Case of BrainGate2 Neural Interface System. [online] Data Science Central. Available from: https://www.datasciencecentral.com/brain-computer-interface-the-case-of-braingate2-neural-interface/
11. Duke Medicine News & Communications. (2016, March 3). Monkeys Drive Wheelchairs Using Only Their Thoughts. [online] Duke University School of Medicine. Available from: https://medschool.duke.edu/news/monkeys-drive-wheelchairs-using-only-their-thoughts
12. Phillip A. (2015, March 3). A paralyzed woman flew an F-35 fighter jet in a simulator — using only her mind. [online] The Washington Post. Available from: https://www.washingtonpost.com/news/speaking-of-science/wp/2015/03/03/a-paralyzed-woman-flew-a-f-35-fighter-jet-in-a-simulator-using-only-her-mind/
13. Popkin BM, D’Anci KE, Rosenberg IH. Water, hydration, and health. Nutr Rev. 2010 Aug;68(8):439-58. doi: 10.1111/j.1753-4887.2010.00304.x.
14. Governatori L, Scampoli A, Culiersi C, Bernardinelli P, Picardi SM, Sarati F et al. Chandelier-assisted scleral buckling: A literature review. Vision (Basel). 2023 Jun 28;7(3):37489326. doi: 10.3390/vision7030047.
15. ALZFORUM. (2010, May 21). Deep-Brain Stimulation: Decade of Surgical Relief, Not Just for PD. [online] Alzforum.org. Available from: https://www.alzforum.org/news/research-news/deep-brain-stimulation-decade-surgical-relief-not-just-pd
16. Bourzac K. (2010, April 19). Brain Interfaces Made of Silk. [online] MIT Technology Review. https://www.technologyreview.com/2010/04/19/204716/brain-interfaces-made-of-silk/
17. Heyes, C. (2016a). Blackboxing: social learning strategies and cultural evolution. Philos. Trans. R. Soc. B 371, 70–76. doi: 10.1098/rstb.2015.0369