Chapter 6

Brain-Computer Interfaces: Brain Chip From Past to Present

Şeyma Nur Çevik[1]

Sezin Güleryüz[2]

Abstract

Brain-computer interface (BCI) is a mechanism that enables individuals to manipulate and control computers or other technological devices by utilizing their brain activities. This technology involves receiving and analyzing brain signals, which are then transformed into commands that can be easily conveyed to intelligent devices, enabling them to perform specific operations. This investigation analyses the evolution of brain chips as brain-computer interfaces from the past to the present. Brain implants and chips serve as apparatus for interfaces, transmitting information through physical interaction with neurons in the brain. No changes in content have been made. The language used is clear, objective, and value-neutral, with a formal register and precise word choice. The structure is clear, with a logical flow of information and causal connections between statements. The text is free from grammatical errors, spelling mistakes, and punctuation errors. Brain-chip interfaces provide individuals with the opportunity to comprehend and interact with their surroundings. The given text strictly conforms to the traditional format, encompassing standard academic divisions and consistent citation of the author and institution. This research employs a method of historical investigation to analyze the development of brain chips over time, spanning from the past until the present era.

1 Master Student, Bursa Uludag University, seymanur.cevikk9@gmail.com, ORCID: 0009-0001-1951-1818

2 Assistant Professor, Bartın University, Management and Information Systems Department, sguleryuz@bartin.edu.tr, ORCID: 0000-0002-9858-7115.

https://doi.org/10.58830/ozgur.pub426.c1850

1. Introduction

Recently, microelectromechanical systems have become increasingly popular in biomedicine. The development of micromachining and microelectronics technologies has led to the creation of new microelectromechanical systems that aim to achieve scientific, diagnostic, and therapeutic goals. The use of microchips to record neuronal activity has undergone significant development, resulting in a highly sophisticated technology with considerable potential for innovative applications in this field (Vassanelli, 2011).

It is a fact that current supercomputers cannot match the cognitive abilities of the human brain. However, experts predict that within ten years, the next generation of supercomputers will have the necessary computational power to do so (Moravec, 1997). Brain-computer interfaces (BCIs) assess the signals and activity of the brain, subsequently empowering users to manipulate devices solely through their cognitive processes by converting said signals into commands for computers. These devices entail swiftly progressing technology that integrates diverse technologies, encompassing sensors, techniques for processing signals, algorithms for machine learning, and applications or software designed for control (Savic & Aricò, 2023).

The Brain-Computer Interface (BCI), also referred to as the Brain-Machine Interface (BMI), is a mechanism that facilitates the interaction and/or regulation between the human brain and external apparatus. Examples of these external devices encompass wheelchairs, computers, robotic arms, and muscle-stimulating devices. Primarily, the objective of BCI is to identify and examine cerebral signals that depict an individual, subsequently transforming these signals into instantaneous instructions for the aforementioned devices (Alkaff et al., 2023).

Brain-computer interfaces are responsible for enabling interaction between artificial devices and humans. In the past, human-machine interfaces heavily relied on human motor control. However, the purpose of interfaces has been transformed by the emergence of powerful computers, innovative microchips, microstimulation technology for neural tissue interaction, and the rapidly progressing field of neuroscience, accompanied by signal detection algorithms. They now rehabilitate motor or sensory function (Kubler & Neumann, 2005). BCIs, whether they are implantable or non-implantable, capture brain signals related to cognitive processes or functional motor movements and utilize these signals to regulate a computer, a robotic arm, or any other external apparatus (Canny et al., 2023).

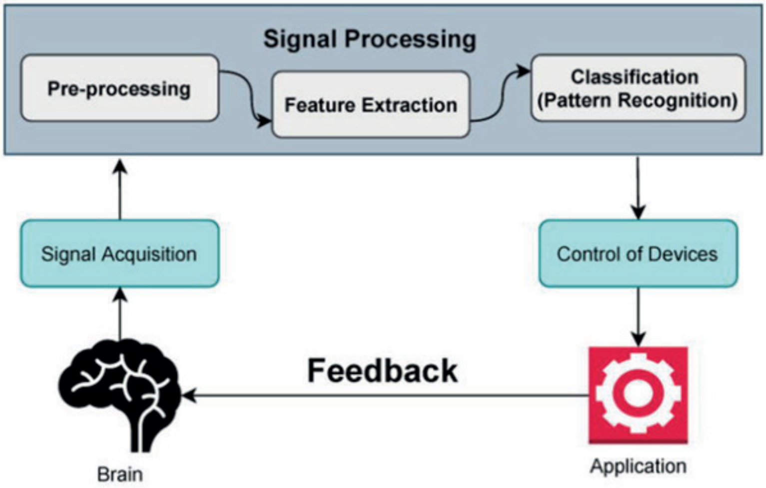

Fig. 1. The basic architecture of the BCI system (Mridha et al., 2021).

As depicted in Figure 2, BCIs are intricate systems designed to receive and decipher neural signals emanating from the brain. These systems meticulously analyze and encode said signals, subsequently transforming the encoded information into actionable commands that are then transmitted to a designated device for their intended purpose. The BCI system comprises a convergence of diverse functions that collectively enable the recognition, encoding, and transformation of neural signals into executable commands. This comprehensive system is composed of four fundamental steps: (a) signal acquisition, (b) feature extraction, (c) translation of the feature, and (d) device output. These constituent components collaboratively operate sequentially to facilitate the seamless interaction between the user and the BCI system (Alkaff et al., 2023).

Recent technological advancements have enabled the creation of brain chip implants, which are designed to improve cognitive functions. These devices interact with the neural connections of the brain and are currently being developed for individuals with therapeutic needs. However, as scientific progress continues, it is anticipated that their utilization will expand in the future to enhance cognitive capacity. As a result, the future use of brain chip implants presents numerous research opportunities for scientists, as it holds the potential to enhance cognitive performance in individuals who do not require therapy (Marinkovic, Marinkovic & Jelic, 2023).

1.1. The History of Brain Implants

On the 26th day of January in the year 1781, Galvani executed a renowned scientific experiment, commonly known as the "first experiment", in which he caused the extremities of a frog to contract, triggered by an electric discharge from a distance (Bresadola, 1998). Galvani's initial work did not seem sufficient to detect the disruptions caused by powerful electrical discharges on the neuromuscular system. In his experiment, Galvani conducted a comparison between the impacts of electrical stimulation on a frog by establishing a connection with one nerve and detaching the other. He demonstrated the inclusion of a nerve property within the framework of neuroelectricity theory, the phenomenon under discussion is the capacity of nervous tissue to transmit electrical impulses with different levels of independence. Specifically, this result was found to be consistent with certain assumptions of neuroelectric theory (Piccolino, 2006).

Galvani began his experiments to substantiate the neuroelectric theory and validate its results. In 1797, Galvani was able to induce muscular contractions in a pair of frog legs using a method in which a single nerve was used to make a connection between two specific points on another nerve (Piccolino, 2006).

In the year 1870, the partnership between Eduard Hitzig and Gustav Fritsch achieved the feat of instigating the movement of canines by applying electric current to specific regions of the cerebral cortex (Hagner, 2012). Hitzig observed that the application of electrical stimulation to a person's cerebral cortex resulted in the movement of their eye organs. To substantiate his findings, Hitzig conducted an experimental study on a rabbit. Subsequently, in collaboration with Fritsch, a systematic study of applying electrical stimulation to the dog encephalon was carried out (Thomas & Young, 2010).

Fritsch and Hitzig's exhibition of the cerebral cortex's electrical excitability is widely acknowledged as a noteworthy contribution to the realm of scientific understanding. The primary importance of their investigation resides in its role in proposing distinct functions in various areas of the cerebral hemisphere. As such, Fritsch and Hitzig's work served as a pioneering effort for subsequent investigations into the physiology of the brain (Thomas & Young, 2010).

Psychologists frequently refer to the research carried out by Gustav Fritsch and Eduard Hitzig in 1870, which is widely recognized as a groundbreaking investigation into the utilization of electrical stimulation on the human brain (Thomas & Young, 2010). This research has stimulated interest in the study of empirical neurophysiology and has enabled scientists to redefine the relationship between cerebral impairment and mental disorders (Hagner, 2012).

Roberts Bartholow's experiment conducted in 1874 is widely acknowledged as the inaugural demonstration of motor excitability. During this seminal study, stimulating electrodes were employed to elicit stimulation in the cortical region of the human brain. Bartholow skillfully inserted stimulating electrodes through a malignant opening in the cerebrum of a young woman named Mary Rafferty to maneuver the patient's physical form. Consequently, this particular endeavor marked the first manifestation of the neural network's capacity for motor excitability within the human brain (Harris & Almerigi, 2009).

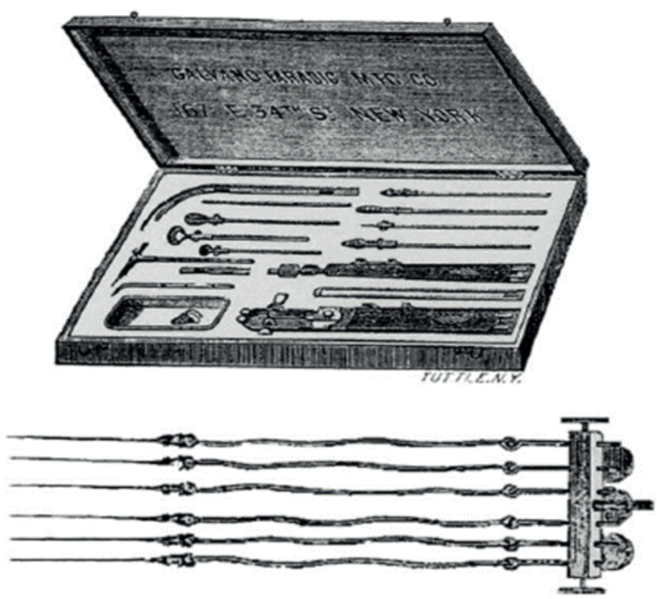

Fig. 2. Various forms of electrodes and electrolytic needles (Bartholow, 1872a).

The metallic bars positioned on both ends of the device exhibit a translational motion in conjunction with the coil, thereby enabling the movement of the metallic rods when the coil oscillates. Each distinct rod forms an electrical connection with one extremity of the coil and is additionally electrically linked to the coil through the metallic supports (Bartholow, 1872).

The descriptions of Bartholow's experiments suggest that the investigations aimed to examine the excitability of the cortical region and its localization (Harris & Almerigi, 2009).

In 1924, Hans Berger became the first person in history to successfully document electroencephalographs (EEGs) (Haas, 2003). The study of electroencephalography (EEG) is a major investigation into the measurement of brain activity. In 1924, by using a vacuum tube amplifier (which amplifies the electric current by a factor of 100), it was possible to obtain a precise and readable electrical trace from the surface of the brain of a patient who had suffered a head injury. K. Berger continued to refine the results over several years. Berger simultaneously exhibited the disparity between brain waves in a state of repose and brain waves while engaging in diverse cognitive activities (commonly referred to as alpha waves or Berger waves). He also successfully demonstrated that the electrical activity surrounding the brain tumor had stopped, as well as the differences between brain activity during sleep and cognitive processing (Kaplan, 2011).

Presently, the application of electroencephalography (EEG) apparatus is considerably efficacious in the domains of neurology, critical care, psychiatry, and experimental psychology (Kaplan, 2011). The researcher used the terms alpha and beta waves (alternatively referred to as Berger waves) in his research. Berger also studied electroencephalogram (EEG) recordings of people of different ages and genders.

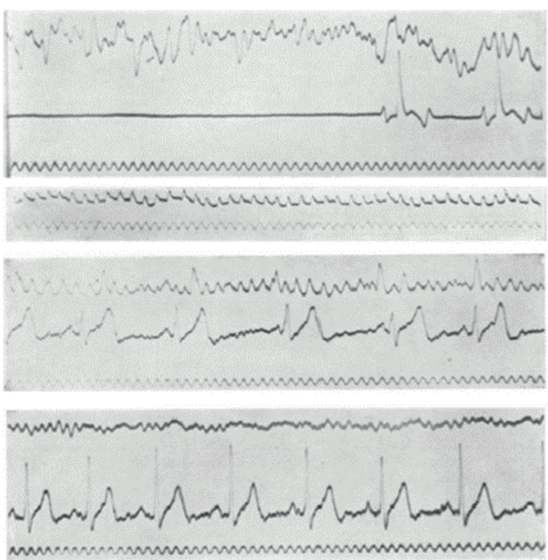

Fig. 3. Examples of EEG (Berger, 1929).

As part of his empirical efforts, Berger noted the changes in brain waves that occur during cognitive processes and sleep. Today, the use of EEG has become commonplace in the detection of disease in various fields, including neurology and psychiatry (Incel, Adanir & Sevmez, 2020).

Deep brain stimulation (DBS) originated from the field of neurostimulation techniques. This area of study has experienced global expansion since the 1940s and has proven to be a valuable therapeutic intervention for individuals with neurological and psychiatric conditions resistant to alternative treatments (Gardner, 2013). During the 1960s, advancements in neurostimulation technologies began to reveal the curative impacts of neurostimulation to many medical practitioners (Gardner, 2013).

During the early 1960s, Medtronic, an expanding manufacturer of medical equipment, unveiled the inaugural pacemaker that was accessible for acquisition within the marketplace. In a similar vein, a contingent hailing from California employed cardiac pacemakers to elicit stimulation within designated sections of the cerebral cortex. In their study, Hosobuchi et al. (1973), performed ablation surgery guided by stereotactic techniques to alleviate chronic pain in patients. To address the inadequate response to conventional treatments, deep brain stimulation (DBS) was tested on multiple individuals. The thalamus was surgically targeted for precise electrode implantation, which was subsequently linked to a pacemaker device, as reported by Hosobuchi et al. (1973). The study conducted by Hosobuchi demonstrated that pain relief was achieved in three out of the four initial participants (Gardner, 2013).

The enduring implantation of electrodes in the cerebral cortex of the animal permits the examination of brain activity for a prolonged duration devoid of the usage of anesthesia (Delgado, 1955). Delgado, the scientist at the forefront of cerebral microchip technology, has developed a device capable of receiving and transmitting stimuli from nerve cells, an electronic instrument with the ability to manipulate cognitive abilities (Horgan, 2005). Electrodes specifically designed to monitor and regulate behavior and physical coordination, as shown in Figure 3, have been surgically implanted in primates, cats, and Homo sapiens.

Fig. 4. The moment when Delgado used the radio to electrically stimulate the brain of the bull (Delgado, 1981).

Successful implantation of these electrodes has been maintained for over two years. A wide range of electrodes have been inserted into the anatomy of cats, primates, great apes, cattle, and even Homo sapiens, demonstrating the ability to manipulate both mental cognition and physical abilities at the touch of a button (Horgan, 2005).

In 1963, in a bullfighting arena in Spain, an impressive bovine specimen, equipped with a cerebral apparatus, began an attack on Delgado. Afterward, however, the said animal stopped its advance and changed its trajectory, all in response to Delgado's communication. Although Delgado's signaling did not succeed in suppressing the bull's innate propensity for aggression, it did succeed in forcing the creature to turn to the left (Horgan, 2005).

Delgado's accomplishments have cleared the path for the advancement of brain implant technology, a field that is presently assisting individuals afflicted with neurological conditions like epilepsy, Parkinson's disease, and dystonia (Horgan, 2005).

In the 16th century, Volta initially inspired a sense of optimism among the hearing-impaired by proposing the possibility of providing them with new hearing organs. By applying an electric current to the skull of individuals, Volta carefully observed their ability to perceive auditory stimuli. This technique was later successfully applied to people with hearing impairments, leading to reports of auditory hallucinations. In the mid-20th century, the practice of implanting electrodes in animals and humans gained momentum. Djourno and Eyries, renowned pioneers in the field of electrophysiology, conducted a groundbreaking experiment in which an electronic cochlea was implanted in a patient suffering from deafness caused by a cholesterol-induced tumor. Although the patient was unable to hear speech, he was able to detect environmental sounds (House & Urban, 1973).

The responsibilities of the synthetic internal auditory system include (1) electronics (hardware); (2) tissue acceptance; (3) excitation of small, distinct nerve fibers; (4) persistence of electrical currents in tissue and electrodes; and (5) auditory detection and stimulus encoding (Simmons & Calif, 1969). In the year 1961, William House executed the inaugural surgical intervention for cochlear implantation, whereby he introduced a solitary wire, followed by a 5-wire electrode array, into the scala tympani area of the cochlea belonging to an individual afflicted with auditory impairment (House, 1976). Now, after more than five decades, cochlear implants have become a widely accepted medical intervention for restoring hearing function in individuals with congenital deafness and those who have experienced hearing loss (Dorman & Parkin, 2015).

In the mid-1970s, a significant transformation occurred in the field of integrated circuits. During this period, it became possible to construct a computer using only ten thousand components, even though the smallest details approached a tiny size of 3 micrometers. However, the number of impurity atoms defining these small chips had decreased to such an extent that the statistical distribution posed a risk of making many components obsolete. The dwindling number of signaling electrons worsened the situation. Atoms were able to traverse the crystal due to the electrical gradients across the narrow gaps, which disturbed the circuit. The risk of signal distortion increased as the wires became closer. As a result, the chips now have many connections, making external connections unnecessary. An analysis of computer development shows a rapid triumph over numerous challenges. The progress of chips has not only persevered but has also accelerated significantly. The implementation of shorter wavelength light has successfully improved the process of impurity implantation. Voltage levels have been reduced, contributing to increased efficiency. Furthermore, advancements in insulator technology and optimized shielding designs have further improved overall performance. As stated by Moravec (1997), transistor designs have undergone significant enhancements, such as the use of non-radioactive packaging materials, denser pin patterns, and improved heat sinks.

In 1996, a revolutionary development took place in the field of neuroscience. Specifically, neurotrophic electrodes were surgically implanted in the body of a paralyzed individual. This innovative procedure allowed the individual to regain control of their motor functions, giving them the ability to manipulate a computer cursor with great precision and accuracy. Researchers Philip Kennedy and Roy Bakay presented a brain implant that produces amplified neurological stimuli to facilitate voluntary motor activity. In 1998, the aforementioned patient received the implant and developed the ability to manipulate a computer cursor through learned motor coordination (Kennedy & Bakay, 1998).

In 1997, deep brain stimulation was first used to treat the tremor associated with Parkinson's disease. The use of this method has led to long-term improvements in patients' health (Benabid, 2003). Deep brain stimulation mimics the effects of a brain lesion without damaging brain tissue. The implementation of this methodology has resulted in a notable enhancement in the motor capabilities of individuals suffering from Parkinson's disease who do not exhibit any positive response to traditional medical measures (Deep-Brain Stimulation for Parkinson's Disease Study Group, 2001).

In 2002, the US Food and Drug Administration (FDA) approved the application of deep brain stimulation (DBS) as a remedial measure for those afflicted with Parkinson's disease. DBS has also been authorized for the management of dystonia (Gardner, 2013).

In 2005, the BrainGate initiative developed a brain-computer interface that allowed a tetraplegic individual to manipulate a robotic arm with success. The experiment aims to assist individuals diagnosed with tetraplegia in controlling a computer cursor and other devices using their cognitive processes. This would enable them to use communication tools, such as email, by simply imagining hand gestures (Bogue, 2010).

Thanks to the pioneering efforts of Cyberkinetics Neurotechnology, a groundbreaking nine-month human trial was conducted. During the trial, a patient was able to use an artificial hand through the implementation of a chip implant. The BrainGate implant, comprising 96 electrodes, was surgically implanted into the patient's right anterior central gyrus, a region within the motor cortex that is closely linked to arm mobility. This groundbreaking technique enabled the patient to exert control over a robotic arm, manipulate a computer cursor, and manipulate television functions solely through the power of their cognitive thoughts and volitional desires (Arafat, 2013). In 2012, a woman was able to drink from a container using only her thoughts thanks to the development of a BrainGate mechanized limb (Hochberg et al., 2012).

In 2016, Elon Musk founded Neuralink intending to develop cutting-edge brain-computer interfaces that have superior data transmission capabilities (Fiani et al., 2021). The interface provided by the Neuralink chip enables the transmission of signal information from an implanted electrode array to process brain signals. This transmission facilitates the transfer of these signals to a receiving device, such as a computer. The chip can extract data from brain signals and use it to generate activity. In addition, during the implantation process of the Neuralink Brain-Computer Interface, a total of approximately 3072 electrodes are meticulously positioned by a robotic system. These electrodes are used to convert brain signals into data, helping to facilitate human interaction and control of a wide range of devices (Jawad, 2021).

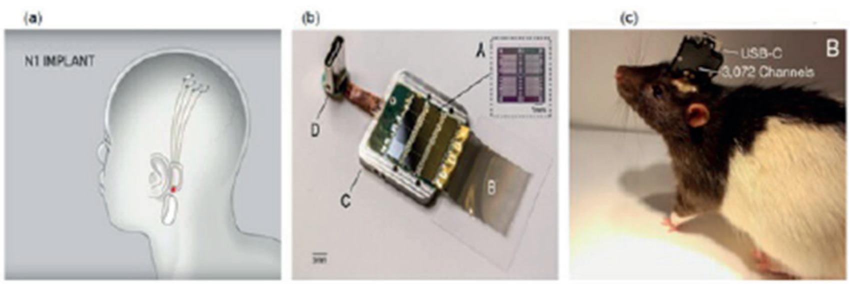

Fig. 5. Neuralink Company has developed a device that can be implanted in humans. The device is designed with a USB-C interface for BCI. The experimentation of Neuralink's BCI in a rat model has been conducted (Dadia & Greenbaum, 2019).

Neuralink's recently developed neurointerface has great potential to serve as the next brain-machine interface for both research and treatment. The use of invasive brain-machine interfaces, such as Neuralink, will allow individuals to interact directly through the medium of their thoughts (Pisarchik et al., 2019). Neuralink aims to alleviate a wide range of brain disorders and improve memory and cognitive performance. Accordingly, this microchip has the potential to alleviate depression, anxiety, and various other psychiatric disorders (Fadziso, 2020). Neuralink, the brain-computer interface project led by Elon Musk, aims to enhance memory and establish a means of communication with computers and devices by being surgically inserted into the human brain (Gurtner, 2021). The application for a human trial by Neuralink, which had been rejected by the United States Food and Drug Administration (FDA) in the past, has now gained approval for a second trial. It is noteworthy, however, that this particular trial, despite reportedly occurring, has not been registered on ClinicalTrials.gov, an online data repository overseen by the National Institutes of Health (NIH) in the United States (Drew, 2024). In 2018, three patients were able to walk with the help of wireless spinal cord implants. A new technological innovation has been developed that enables individuals with chronic tetraplegia to stand upright and walk. This objective is realized via a digital connection that establishes a natural connection between the cerebral cortex and the spinal cord. The device responsible for this breakthrough is called the brain-spinal cord interface (BSI), which includes fully embedded stimulation systems that target the spinal cord (Lorach et al., 2023).

The patient's ability to control the movement of their lower limbs and perform actions such as standing upright, walking, and climbing stairs has been recorded. This has expedited the patient's neurological recovery. The patient successfully restored their capacity to ambulate by using a walking aid, even when they were not actively utilizing the device. This digital mechanism has helped to regain control over the body after paralysis (Lorach et al., 2023).

2. Conclusion

BCIs has surfaced as a mechanism that enables the exchange of information between the brain and the encompassing external milieu. The introduction of BCIs has introduced a mechanical framework for scrutinizing neural activities and transforming them into neural information. This framework has opened up numerous avenues for effortless engagement with diverse mechanisms (Ye et al., 2024). BCIs are technological systems that allow for the interaction between the brain and external devices, thereby facilitating the acquisition of data and the stimulation of neurons. Depending on the placement of electrodes, BCIs can be categorized as either invasive or non-invasive, with the former involving implantation within the brain and the latter involving placement on the scalp. Primarily utilized in medical contexts, these interfaces have proven invaluable in the diagnosis of neurological conditions and the provision of neurostimulation. The utilization of BCIs in neurostimulation has demonstrated efficacy in the identification of ailments such as epilepsy and sleep disorders, in addition to facilitating brain imaging for the detection of anomalies. Furthermore, BCIs have exhibited considerable success in the treatment of illnesses like Parkinson's disease and obsessive-compulsive disorder, particularly when traditional pharmaceutical interventions have proven inadequate. Notably, the popularity of BCIs has surged in recent years owing to their reduced cost and smaller size, making them more accessible to a broader population. Additionally, advancements have been made in minimizing the dimensions of invasive BCIs, thereby enhancing patient safety. Prominent companies like Neuralink are actively engaged in research and development efforts aimed at creating systems capable of reading and stimulating individual neurons in the brain, with the ultimate goal of democratizing neurotechnology (López Madejska et al., 2024).

BCIs are classified into two primary categories: implantable, which are surgically implanted, and non-implantable, which are applied externally. Implantable electrodes provide high precision and superior capability in executing intricate commands compared to surface-based electrodes. However, non-implantable electrodes, such as scalp patches, are considered safer and more widely accepted. Despite their limitations in terms of accuracy and range, non-implantable alternatives are indispensable for users who do not have any health conditions. The process of acquiring signals encounters obstacles such as power interruptions and artifacts caused by eye movements. These challenges are mitigated through the application of EEG and cortical EEG models for analysis purposes. Re-encoding techniques are employed to transform decoded data into specific tasks, such as controlling the movements of a robotic arm. BCIs can be integrated with various fields of engineering by utilizing diverse encoding methods. The feedback process involves the reception of sensory input, which is essential for managing multi-modal perception and is crucial for the successful implementation of BCIs (Qin, 2024).

The connection between the brain and the chip is a complex network that allows for interaction between the chip and neurons. This particular system facilitates bidirectional signal transmission, allowing for communication between the brain and the computer via the utilization of a chip. As a result, the computer can process messages generated by brain cells. It should be noted that this interaction is bidirectional, as the computer also can transmit messages back to the chip (Saba et al., 2017).

The benefits of brain chips are as follows: they facilitate efficient performance. Researchers have found that the insertion of the chip into the human brain is reliable and adaptable, making it significant in enabling individuals to utilize their brain function. Brain chips are also endowed with self-regulation, allowing them to assist individuals in enhancing their memory voluntarily. Brain chips are versatile and can be effectively applied in diverse circumstances. They can also be personalized to cater to the distinct requirements of each individual. These chips enhance cognitive abilities, ensuring productivity. Furthermore, they provide a sense of security by safeguarding an individual's memory from potential loss. The drawbacks of brain chips include the high costs of manufacturing and potential risks associated with the implantation procedure (Saba et al., 2017).

Advanced brain-chip interfaces with high resolution enable the investigation of cerebral functionalities at sub-cellular levels. Technological advancements have allowed for the collection and documentation of vast amounts of data from various cerebral domains. To decode this data, certain apparatuses were necessary (Mahmud et al., 2017).

The development of brain chip implants represents a groundbreaking advancement in the fields of engineering and neuroscience, particularly for individuals afflicted with neurological disorders. By utilizing nano-technology, scientists can fabricate diminutive and superior chips, making brain chip technology a more dependable alternative. One of the main advantages of this innovation is that it restores bodily functions for patients, making rehabilitation efforts easier (Saba et al., 2017). In recent times, the emergence of cutting-edge methods in device fabrication, namely 3D printing and injection molding, has facilitated the efficient creation of devices. The implementation of standardized protocols during the manufacturing process of chips can effectively minimize variations among chips and offer accessible platforms that cater to the needs of novice users (Ahn & Kim, 2024).

Intracortical brain-computer interfaces represent an innovative technological advancement employed to reinstate both motor control and communication capabilities in persons afflicted with disabilities. By deciphering cerebral movement signals, IBCIs facilitate the regulation of paralyzed limbs, thereby enabling individuals to engage in a myriad of tasks including controlling robotic appendages, transcribing manual gestures into written language, and comprehending spoken discourse (Deo et al., 2024).

When it comes to the development of brain-computer interfaces, it is crucial to adopt a multidisciplinary methodology that encompasses a comprehensive analysis of cerebral functions and the symbiosis between the nervous system and neuroprosthetic devices (Vassanelli, 2011). The effectiveness of brain-computer interfaces in the forthcoming times will rely on their capacity to furnish individuals with valuable skills, their enduring safety, and the degree of convenience they offer (Daly & Wolpaw, 2008).

These advances have the potential to enhance the well-being of many people. They can improve individuals' standard of living and enable them to lead more productive and purposeful lives (Maguire & McGee, 1999).

The ever-changing technical environment is a result of the rapid progress in technology. The main goal of this article is to bring together previous research on brain-computer interfaces and tackle the obstacles faced, thus contributing to the current global applications in this domain. In future research efforts, the integration of deep transfer learning and neural networks is anticipated to enhance the potential of brain-computer interface applications, thereby providing support to a larger population (Qin, 2024).

BCIs can transform how we interact with technology, enabling more intuitive and seamless control of devices through direct brain signals. This could lead to advances in areas such as VR, AR, and immersive gaming experiences. However, there are still many technical, ethical, and sociological issues that need to be addressed before BCIs can be widely adopted. These include issues related to data privacy, security, reliability, and accessibility. Despite these challenges, the future of brain-computer interfaces appears promising, with the potential to profoundly impact various aspects of our lives.

Kaynakça

Ahn, S. I., & Kim, Y. (2024). On-chip physiological mimicry of neurovascular unit: Challenges and perspectives. *Neural Regeneration Research,* 19(3), 499-500.

Alkaff, Z. A., Malim, N. H. A. H., Sumari, P. & Abdullah, J. M. (2024). Applications of brain computer ınterface in a present healthcare setting. N. H. Kashou (Ed.), *New isights in brain-computer interface systems.* (pp: 1-25). London: Intechopen.

Arafat, I. (2013). Brain-computer interface: past, present & future. *International Islamic University Chittagong (IIUC), Chittagong, Bangladesh*, 1-6.

Bartholow, R. (1872a). The electrical room of the Good Samaritan Hospital. *The Clinic,* Cincinnati, 2, 86–89.

Benabid, A. L. (2003). Deep brain stimulation for Parkinson's disease. *Current Opinion İn Neurobiology*, *13*(6), 696-706.

Berger H (1929) Über das elektroenkephalogramm des menschen. *Arch Psychiatr Nervenkr;* 87(1), 527–570.

Bogue, R. (2010). Brain-computer interfaces: Control by thought. *Industrial Robot: An International Journal*, 37(2), 126-132.

Bresadola, M. (1998). Medicine and science in the life of Luigi Galvani (1737–1798). *Brain Research Bulletin*, *46*(5), 367-380.

Canny, E., Vansteensel, M. J., van der Salm, S. M., Müller-Putz, G. R. & Berezutskaya, J.

(2023). Boosting brain–computer interfaces with functional electrical stimulation:

Potential applications in people with locked-in syndrome. *Journal of NeuroEngineering and Rehabilitation*, *20*(1), 157.

Dadia T, Greenbaum D. (2019). Neuralink: The ethical 'rithmatic of reading and writing to the brain. *AJOB Neurosci*. 10(4), 187-189.

Daly, J. J., & Wolpaw, J. R. (2008). Brain–computer interfaces in neurological rehabilitation. *The Lancet Neurology*, *7*(11), 1032-1043.

Deep-Brain Stimulation for Parkinson's Disease Study Group. (2001). Deep-brain stimulation of the subthalamic nucleus or the pars interna of the globus pallidus in Parkinson's disease. *New England Journal of Medicine*, *345*(13), 956-963.

Delgado, J. R. (1955). Evaluation of permanent implantation of electrodes within the brain. *Electroencephalography and Clinical Neurophysiology*, *7*(4), 637-644.

Deo, D. R., Willett, F. R., Avansino, D. T., Hochberg, L. R., Henderson, J. M. & Shenoy, K. V. (2024). Brain control of bimanual movement enabled by recurrent neural networks. *Scientific Reports*, *14*(1), 1598.

Dorman, M. F., & Parkin, J. L. (2015). The role of the Utah Artificial Ear project in the development of the modern cochlear implant. *Cochlear Implants International*, *16*(2), 1-11.

Drew, L. (2024). Elon Musk's Neuralink brain chip: What scientists think of first human trial. *Nature*.

Fadziso, T. (2020). Why Neuralink will Change Humanity Forever?. *Asian Journal of Humanity, Art and Literature*, *7*(1), 69-78.

Fiani B, Reardon T, Ayres B, Cline D & Sitto SR. (2021). An examination of prospective uses and future directions of Neuralink: the brain-machine interface. *Cureus,* 13(3).

Food and Drug Administration (FDA) (1997) Premarket notification: Implantable deep brain stimulation for the treatment of tremor due to Parkinson's disease and essential tremor.

In: *Neurological devices panel meeting of the Medical Devices Advisory Committee*, Gaithersburg, MD, 14 March. Washington, DC: Miller Reporting Company.

Gardner, J. (2013). A history of deep brain stimulation: Technological innovation and the role of clinical assessment tools. *Social Studies Of Science*, *43*(5), 707-728.

Gurtner, D. (2021). Neuralink and beyond: Challenges of creating an enhanced human.

In FOLIA - Fribourg Open Library and Archive. https://folia.unifr.ch/unifr/documents/309154

Haas, L. (2003). Hans Berger (1873–1941), Richard Caton (1842–1926) and electroencephalography. *Journal Of Neurology, Neurosurgery and Psychiatry*, 74(1), 9.

Hagner, M. (2012). The electrical excitability of the brain: Toward the emergence of an experiment. *Journal of the History of the Neurosciences*, *21(*3), 237-249.

Harris, L. J. & Almerigi, J. B. (2009). Probing the human brain with stimulating electrodes: The story of Roberts Bartholow's (1874) experiment on Mary Rafferty. *Brain and Cognition*, *70*(1), 92-115.

Hitzig, E. (1870). Ueber die galvanischen schwindelempfindungen und eine neue method galvanischer reizung der augenmuskeln [On the galvanic sensations of vertigo and a new method of galvanic irritations of the eye muscles]. *Berliner Klinische Wochenschrifi, 2,* 137-138.

Hochberg L. R., Bacher, D., Jarosiewicz B, Masse, N.Y., Simeral, J. D., Vogel, J., Haddadin, S., Liu, J., Cash, S. S., van der Smagt, P. & Donoghue J. P. (2012). Reach and grasp by people with tetraplegia using a neurally controlled robotic arm. *Nature, 485*(7398), 5-372.

Horgan, J. (2005). The forgotten era of brain chips. *Scientific American*, *293*(4), 66-73.

Hosobuchi, Y., Adams, J. E. & Rutkin, B. (1973). Chronic thalamic stimulation for the control of facial anesthesia dolorosa. *Archives of Neurology,* 29(3), 158–161.

House, W. F., & Urban, J. (1973). Long term results of electrode implantation and electronic stimulation of the cochlea in man. *Annals of Otology, Rhinology & Laryngology*, *82*(4), 504-517.

House, W.F. (1976). Cochlear implants. *Annals of Otology, Rhinology & Laryngology, 85*(27), 1–93.

İnce, R., Adanır, S. S., & Sevmez, F. (2021). The inventor of electroencephalography (EEG): Hans Berger (1873–1941). *Child's Nervous System*, *37*, 2723-2724.

Jawad, A. J. (2021). Bioethics of medical devices based on brain computer interfaces (BCI). *Journal of Clinical Research & Bioethics,* 21(8).

Kaplan, R. M. (2011). The mind reader: The forgotten life of Hans Berger, discoverer of the EEG. *Australasian Psychiatry*, *19*(2), 168-169.

Kennedy, P. R. & Bakay, R. A. (1998). Restoration of neural output from a paralyzed patient by a direct brain connection. *NeuroReport*, *9(*8), 1707–1711.

Kübler, A. & Neumann, N. (2005). Brain-computer interfaces—The key for the conscious brain locked into a paralyzed body. *Progress in Brain Research*, *150*, 513-525.

López Madejska, V. M., López Bernal, S., Martínez Pérez, G. & Huertas Celdrán, A. (2024).

Impact of neural cyberattacks on a realistic neuronal topology from the primary visual cortex of mice. *Wireless Networks*, 1-15.

Lorach, H., Galvez, A., Spagnolo, V., Martel, F., Karakas, S., Intering, N., Vat, M., Faivre, O., Harte, C., Komi, S., Ravier, J., Collin, T., Coquoz, L., Sakr, I., Baaklini, E., Hernandez-Charpak, S. D., Dumont, G., Buschman, R., Buse, N., Denison, T., van Nes, I., Asboth, L., Watrin, A., Struber, L., Sauter-Starace, F., Langar, L., Auboiroux, V., Carda, S., Chabardes, S., Aksenova, T., Demesmaeker, R. & Charvet, G. (2023).

Walking naturally after spinal cord injury using a brain–spine interface. *Nature*, 1-8.

Maguire, G. Q. & McGee, E. M. (1999). Implantable Brain Chips? Time for Debate. *The Hastings Center Report*, *29*(1), 7–13.

Mahmud, M., Cecchetto, C., Maschietto, M., Thewes, R. & Vassanelli, S. (2017, December).

Towards high-resolution brain-chip interface and automated analysis of multichannel neuronal signals. In *2017 IEEE Region 10 Humanitarian Technology Conference (R10-HTC)* (pp: 868-872). IEEE.

Marinković, D., Marinković, T. & Jelić, A. (2023). Perspectives and Challenges in Cognitive Enhancement Based on the Neurotechnology Approach. In *Conference Proceedings/International Scientific and Professional Conference Politehnika 2023* (pp: 852-855). The Academy of Applied Technical Studies" Belgrade", Belgrade.

Marzullo, T. C. (2017). The missing manuscript of Dr. Jose Delgado's radio controlled bulls. *J Undergrad Neurosci. Educ.*, 15(2), 29-35.

Moravec, H. (1998). When will computer hardware match the human brain. *Journal of Evolution and Technology*, *1*(1), 10.

Mridha, M. F., Das, S. C., Kabir, M. M., Lima, A. A., Islam, M. R. & Watanobe, Y. (2021).

Brain-computer interface: Advancement and challenges. *Sensors*, *21*(17), 5746.

Piccolino, M. (2006). Luigi Galvani's path to animal electricity. *Comptes Rendus Biologies*, *329*(5-6), 303-318.

Qin, Z. (2024). A systematic analysis of wearable devices as brain-computer ınterface based on neuromodulation. *Highlights in Science, Engineering and Technology*, *81*, 306-312.

Saba, G., Khaleel, M. S., Pasha, S. M., Taskeen, S. & Elahi, M. (2017). The future technology brain chip interference. *International Journal Of Engineering Research & Technology*, 5(18).

Savić, A. M., & Aricò, P. (2023). Global excellence in brain-computer interfaces: Europe. *Frontiers in Human Neuroscience*, *17*.

Simmons, F. B. (1969). Cochlear implants. *Archives of Otolaryngology*, *89*(1), 61-69.

Thomas, R. K. & Young, C. D. (1993). A note on the early history of electrical stimulation of the human brain. *The Journal of General Psychology*, *120*(1), 73-81.

Vassanelli, S. (2011). Brain-chip interfaces: The present and the future. *Procedia Computer Science*, *7*, 61-64.

Ye, Y., Wang, Z., Tian, Y., Zhou, T., Zhou, Z., Wei, X., ... & Sun, L. (2023). A brain-to-brain ınterface with a flexible neural probe for mouse turning control by the human mind. *IEEJ Transactions on Electrical and Electronic Engineering*.