

ETHICAL AND SAFETY CHALLENGES OF IMPLANTABLE BRAIN-COMPUTER INTERFACE

Ihab Abdulrahman Satam^{1, 2, *} and Róbert Szabolcsi³

¹Óbuda University, Doctoral School on Safety and Security Sciences
Budapest, Hungary

²Northern Technical University, Technical College, Mechatronics Department
Alhawija, Iraq

³Óbuda University, Kandó Kálmán Faculty of Electrical Engineering, Institute of Electronic and Communication Systems, Department of Measurement Technology and Automation
Budapest, Hungary

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ABSTRACT

The study of brain-computer interfaces (BCIs) holds immense potential across various fields, particularly in Human-Robot Interaction, where invasive BCIs offer precise and direct communication between the human brain and robotic devices. However, the use of invasive BCIs raises significant ethical, safety, and security concerns that must be addressed to ensure their responsible deployment. This research provides a comprehensive analysis of these challenges, offering a unique contribution by proposing a framework for mitigating risks and guiding ethical practices in the development and application of invasive BCIs. Key findings include the identification of critical safety risks, such as infection, tissue damage, and long-term biocompatibility issues, alongside actionable strategies to mitigate these risks through advanced materials, rigorous monitoring, and post-operative care. The study also highlights the security vulnerabilities inherent in invasive BCIs, including unauthorized data access and wireless communication risks, and proposes robust solutions such as encryption, secure authentication, and tamper-resistant designs. Ethically, the research emphasizes the importance of informed consent, privacy protection, and user autonomy, particularly in the context of HRI. It calls for the development of clear ethical guidelines and continuous dialogue among stakeholders to ensure that invasive BCIs are deployed in a manner that respects individual rights and societal values. By integrating these insights, this study contributes to the advancement of invasive BCI technology in Human-Robot Interaction, ensuring that future developments are not only technologically innovative but also ethically sound, safe, and secure. The findings underscore the necessity of interdisciplinary collaboration to navigate the complex challenges of implantable BCIs, paving the way for their responsible integration into human-robot interactions.

KEY WORDS

BCI, invasive, safety, human-robot interaction

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*Corresponding author, η : ihab.satam@uni-obuda.hu; +36 70 344 8585;
Óbuda University, Népszínház 8., H-1081 Budapest, Hungary

INTRODUCTION

Brain-Computer Interfaces (BCIs) are technologies that enable direct communication – eluding conventional channels such as muscles or nerves – between the human brain and external equipment [1]. Typically, these interfaces utilize sensors to identify brain activity, signal processing to decipher the activity, and finally command translation to operate external devices using the signals. While BCIs have many uses, Human-Robot Interaction (HRI) is one prominent use [2]. BCIs use different types of methods for recording signals: non-Invasive such as electroencephalography (EEG) or magnetoencephalography (MEG) or invasive such as Implanted electrodes. There are several application of BCI in Human-Robot Interactions (HRI), These applications is as follows:

- **Robotic Devices control** – with BCIs, users may directly control robotic equipment with brain impulses. This is especially helpful for those who have limited movement since it enables them to use robotic prosthesis or assistive devices to interact with their surroundings,
- **Telepresence and Remote Control** – BCIs enable activities to be carried out without the need for human presence by controlling robots at distant places. Applications for this may be found in domains including hazardous situations, search and rescue, and space exploration,
- **Human-Robot Collaboration Enhancement** – human-robot cooperation can be improved with the use of BCIs. For instance, a BCI can be used to cause a robot to react or behave in a certain way, resulting in a more instinctive and natural relationship [3],
- **Recognitions of Emotions** – potential applications for BCIs include identifying users' emotional states when they engage with robots. The robot may be able to modify its behavior in response to this knowledge, resulting in a more sympathetic and tailored exchange.

There are some challenges regarding the BCI in Human-robot interactions that will be explained in detail later in the next sections. Such challenges are the Quality and noises of the signals [4], this can affect the accuracy and may have an impact on how well user intent is understood. Another challenge is the difference between users which affect their adapting skills to the devices. Finally, ethical consideration is an important factor due to the potential of misuse of brain signals over time. It is important before beginning to mention the previous studies in the BCI field. In this article, the Literature review will be divided into two categories, the first section will be about the Design, Development and application of BCI, Second Part will be about Physiological and Neurological aspect of BCI.

DEVELOPMENT AND APPLICATION OF IMPLANTED BCI

There are several studies regarding the development of BCI in general and implanted BCI in particular. The implanted BCI provide a direct connection between the brain and an external device such as computers or robotic system. The electrodes are surgically implanted in the brain tissue, which allows for accurate, precise and fixed communication. Serrano-Amenos and her team [5] presented a study to determine the highest power use that ensures a skull unit's (SU) thermal safety. The SU is a component of a fully implanted, bi-directional brain-computer interface (BD-BCI) system designed to help people with spinal cord injuries regain their ability to walk and feel their legs. The study estimated that the SU can theoretically use up to 70 mW of power without increasing the temperature of the surrounding tissues over the 1°C thermal safety barrier based on simulations. Based on the model's natural variance in parameters, they calculated that the power budget may be anything from 47 mW to 81 mW. This power budget ought to be adequate to power the SU's fundamental functions, such as cortical stimulation control and the amplification, serialization, and A/D conversion of neural impulses. An essential need for the design of the SU and, consequently, the design of a fully-implantable

BD-BCI system is figuring out the power budget. Qiu et al. [6] proposed a head-implantable, small, wideband antenna for BCI systems. The antenna has a wider bandwidth and a smaller footprint thanks to correctly etched grooves in the ground, which is ideal for wireless communications. Every stage of the alteration of the antenna structure has been explained, along with its impacts and operating mechanism. Using High Frequency Structure Simulator for Industrial, Scientific and Medical Band, and Wireless Medical Telemetry Service bands, the radiation characteristics were calculated and examined in a male-head phantom.

Serrano-Amenos [7] created a decoder to recognize distinct gait patterns from Electroencephalography (EEG) data. The decoder employed a logistic regression-based feature extraction module, which was succeeded by a Fokker-Planck-based Bayesian filter. They used EEG data from two participants walking on a treadmill to assess the decoder's performance offline. They discovered that the decoder's average sensitivity and accuracy were 94% and 99%, respectively, using a leave-one-out cross-validation technique. They also demonstrated that the decoder is appropriate for real-time implementation due to its low computational complexity. Another study established by Plummer et al. [8], an observational, proof-of-concept research was carried out to test the usage of a modified BrainPath® [9] device to implant subcortical microchips in a mouse model. All of the animals survived the treatment and lived for one to three months with a microchip in place with no evident neurological consequences. Histological investigation demonstrated that the implantation of a tiny chip was linked with tissue destruction, tract development, and reactive alterations in the surrounding tissue. After one month, gliosis and hemosiderin-laden macrophages were seen around the tract marks, and after three months, localized cystic cavitation associated with infarcted tissue was visible. Yi et al. [10] presents a research dealing with an implanted wireless 32-channel bidirectional brain machine interface for use with freely moving monkeys. Based on the brain activity report, the system is meant to monitor brain sensorimotor cycles and deliver current stimuli with adjustable duration, frequency, and amplitude to the brain in real time. The battery is charged using a unique ultrasonic wireless power delivery module designed for efficient power delivery into a highly integrated system. The device was successfully tested on a behaving monkey using bench testing and in vivo tests to capture the local field potential oscillation and stimulate the target region at the same time.

PHYSIOLOGICAL AND NEUROLOGICAL ASPECTS OF IMPLANTED BCI

When it comes to studying the application of BCI, the effects related to physiology and neurology of the patient's brain is a -must-be-considered object. Mariska et al. [11] presented an appropriate real-world application of implanted BCIs. They cover the current level of research on implanted BCIs for communication, as well as the medical and ethical consequences of this technology's clinical implementation. They conclude that all BCI stakeholders, including patients from various Amyotrophic Lateral Sclerosis (ALS) related professions, will be required to define procedures for, and influence the process of, appropriate clinical deployment of implanted BCI. Sergio et al. [12] developed and implemented Neural Jamming (JAM), a novel neural hacking technique that prevents neurons from generating spikes. Given the lack of realistic mammalian neural topologies, they created a use case using a Convolutional Neural Network (CNN). The CNN was trained to guide a simulated mouse through a labyrinth, allowing them to apply and assess the effects of JAM on neural activity. The resulting model was transferred to a biological neural architecture, modeling a section of the visual cortex of a mouse. The effects of JAM on both biological and artificial networks are assessed, focusing on how it disrupts spontaneous neuronal activity and impacts the simulated mouse's ability to navigate the labyrinth. The study explores how these disruptions affect neural signaling and task performance, providing insights into the influence of neural interference on behavior and network function. Peter et al. [13] pointed out the important

challenges to neurotechnology translation of implanted BCI. Implanted BCIs are an innovative research and development field that combines neuroscience, engineering, and medical technology [14]. BCI has the potential to significantly improve the quality of life for people suffering from neurological diseases while also enhancing our knowledge of the brain's intricate functioning.

BACKGROUND

Over time, there have been notable developments in the technology of BCI and their integration with human bodies. Along the way, advances in technology, our understanding of brain functions, and ongoing efforts to improve the efficacy and safety of these interfaces have all been significant[15]. Let us continue with a quick synopsis of how BCIs have developed and how they are integrated.

- 1.) **Early EEG and electrophysiology (1920s-1950s):** the study of brain electrical activity dates back to the 1920s, when researchers first started working on brain computer interfaces (BCIs). The electroencephalogram (EEG), which uses electrodes applied to the scalp to monitor brain activity, was first developed in the 1950s.
- 2.) **Invasive Implantation of Electrodes (1970s-1980s):** in the early stages of BCI research, electrodes were surgically implanted into animals' brains by researchers. Human electrode experiments started in the 1970s and 1980s, mostly for medical objectives such as treating epilepsy.
- 3.) **The Development of non-invasive BCI (1990s-2000s):** with the advent of technologies like functional magnetic resonance imaging (fMRI) and MEG, the 1990s witnessed a trend towards non-invasive BCIs. As a non-invasive technique for capturing brain activity, electroencephalography (EEG) gained popularity, opening the door for useful BCI applications.
- 4.) **The spread of EEG Based BCI(2000s – Present):** because EEG-based BCIs are non-invasive, inexpensive, and simple to use, there has been a significant increase in research on them in the 2000s. Applications of BCIs were investigated, including helping people with motor difficulties communicate.
- 5.) **Signal Processing and machine learning development (2010s-Present):** the decoding and interpretation of brain signals has been greatly enhanced by developments in machine learning and signal processing. With the ability to convert brain impulses into more accurate commands, external equipment like computer interfaces and prostheses may now be controlled more effectively.
- 6.) **Creation of Implantable BCIs (2010s-Present):** the possibility of implantable brain-computer interfaces (BCIs) to offer more precise and direct access to neural signals has drawn interest. Enhancing the biocompatibility, durability, and safety of implanted devices is the main goal of research and development.
- 7.) **Neuro-prosthetics and Hybrid BCIs (2010s-Present):** in order to capitalize on the advantages of both techniques, hybrid BCIs integrate invasive and non-invasive procedures. Brain-controlled prosthetic limbs, or neuro-prosthetics, have emerged as a focal point illustrating the usefulness of BCIs in the restoration of motor function.
- 8.) **Exploration of Neural Interfaces for Cognitive Enhancement (Ongoing):** the potential of BCIs for improving cognitive function is still being investigated. Potential uses include brain stimulation, neurofeedback, and memory improvement.
- 9.) **Ethical and Cultural Aspects (Ongoing):** concerns about permission, privacy, and possible abuse of brain data are among the ethical issues surrounding BCIs that are being actively studied and addressed as they grow more sophisticated and incorporated into human bodies.

The development of BCIs is indicative of the dynamic interaction between scientific knowledge, technological progress, and the search for useful applications that might improve human capacities and tackle medical issues. More advancements in the integration of BCIs into the human body are probably in store as a result of ongoing study and collaboration across interdisciplinary domains.

HRI has great promise for the development of BCIs, which might completely transform human-robot cooperation. An outline of the main elements and possible advantages of developing BCIs for HRI is provided here:

- **Communication:** BCIs enable direct communication between humans and robots through brain signals, bypassing traditional input methods like voice or manual control. This can be particularly useful for individuals with physical disabilities, allowing them to control robots with their thoughts, facilitating seamless interaction.
- **Assistive Technology:** BCIs can significantly enhance assistive technologies by enabling users to control robotic devices (e.g., prosthetics or exoskeletons) with their brainwaves. This can offer more intuitive, natural, and efficient control compared to traditional methods, improving the quality of life for people with disabilities.
- **Improved Human-Robot Collaboration:** By using BCIs, robots can better understand and respond to human intentions, allowing for more fluid collaboration. This can enhance productivity in environments like manufacturing, where human-robot teams work together, as well as in complex tasks like medical surgeries or space exploration.
- **Remote Control:** BCIs can allow users to remotely control robots in dangerous or inaccessible environments (e.g., hazardous waste cleanup, underwater exploration, or space missions). Brain signals can provide intuitive control, even when the operator is far from the robot, increasing safety and efficiency.
- **Adaptation and Neurofeedback:** BCIs can adapt to the user's mental state and provide neurofeedback, helping users improve their cognitive functions or control over the robot. For instance, if the user is stressed or distracted, the system can adjust the robot's behavior or provide feedback to help the user regain focus.
- **Synchronization of Mind-Machine:** BCIs enable tight synchronization between the human mind and machine actions. This synchronization can make interactions with robots feel more like an extension of the user's own body, allowing for precise control and more natural movement in tasks requiring fine motor skills.
- **Cognitive Workload Assessment:** By analyzing brain signals, BCIs can assess the cognitive workload of a user while interacting with a robot. This can help adjust the robot's complexity or offer assistance when needed, preventing mental fatigue and optimizing performance for tasks like high-stakes decision-making or complex robotic control.
- **Potential Communication of Brain-to-Brain:** BCIs could open up the possibility of direct brain-to-brain communication between humans or between humans and robots. This could be revolutionary for applications where instant, silent, and efficient communication is needed, such as emergency response teams or collaborative robotic systems in military or rescue operations.
- **Experience Enhancement:** BCIs can be used to enhance user experience by providing real-time feedback based on brain signals. This could be used in gaming, virtual reality, or immersive learning environments where the robot's responses are tailored to the user's mental state, improving engagement and performance.

IMPLANTED BCI TECHNOLOGY

The implanted BCI has advanced significantly, and further research and development efforts are directed on enhancing the devices' efficacy, adaptability, and safety [16-18]. Compared to

non-invasive techniques, implantable BCIs can record neural signals straight from the brain, giving a more precise and in-depth depiction of the user's intents. In order to provide a direct line of communication between the human brain and external systems, such robots, implants known as implantable BCIs, are placed within the brain. Different kinds of implants facilitate this connection for different reasons. Table 1 shows the different type of implants, their functions and their Human-Robot interface:

Table 1. Type of implanted BCIs.

Implant	Functionality	Human-Robot Communication
Microelectrode Arrays	High spatial resolution cerebral activity recording is made possible by microelectrode arrays, which are made up of tiny electrodes inserted into certain brain areas.	The decoding of brain signals associated with motor intentions is a common use for these implants. For instance, impulses corresponding to limb movement can be detected by microelectrode arrays implanted in the motor cortex. Robot control directives can then be generated from these signals.
Neurostimulation Devices	Certain brain areas get electrical stimulation from neurostimulation implants. They can be applied therapeutically to address neurological conditions or regulate brain function.	By modulating brain activity, neurostimulation devices could potentially increase the speed and clarity of communication between humans and robots. This is particularly valuable for tasks requiring fast, responsive actions, such as in emergency situations or real-time control of robotic systems.
Deep Brain Stimulation (DBS) Implants	Used to treat illnesses such as epilepsy and Parkinson's disease by implanting electrodes deep into the brain.	Although DBS implants are not often used to decode neural signals, research is still being done to see whether they may be utilized to modulate brain activity to better communication with external devices and improve cognitive performance.
Wireless Brain Implants	Without the need of physical tethers, wireless implants allow connectivity with external devices. Power sources, transmitters, and sensors are frequently included in them.	BCIs' usability and mobility can be improved via wireless implants. They provide more freedom in daily tasks by enabling people to interact with robots without being limited by physical connections.
Hybrid BCIs	In order to make use of each technology's advantages, hybrid BCIs blend various implant types or both invasive and non-invasive technologies.	The goal of hybrid BCIs is to offer a more flexible and adaptive platform for brain-to-robot communication. For example, implanted electrodes provide finer control, although EEG may be utilized for initial calibration.

By creating a smooth and organic interface, these implanted devices aim to enable people to communicate with robots by enabling them to control and interact with them using their intentions and ideas. In order to increase the efficacy, safety, and dependability of BCIs in the context of human-robot communication, ongoing research endeavors to investigate novel implant technologies and refine current implementations.

SAFETY AND SECURITY CONCERNS OF IMPLANTED BCI

Implanted BCI has great potential. However, like any medical intervention it has safety risks [19]. Table 2 shows the most common safety risks regarding the implanted BCIs:

Table 2. Safety Risks of Implanted BCIs (continued on p.89).

Category	Risks	Mitigations
Infection	There is a higher chance of infection at the surgical site when gadgets are implanted into the body. Localized problems or, in more severe circumstances, systemic infections might result from infections.	Using antimicrobial materials, post-operative care, and strict adherence to aseptic surgical practices can all help lower the risk of infection.
Inflammation and Damage of Tissues	An implanted device may cause an inflammatory reaction that might cause scarring or tissue damage around the implant site.	To reduce tissue reaction and inflammation, research is concentrated on creating biocompatible materials and coatings. To determine the implant's long-term effects on the surrounding tissues, long-term investigations are necessary.
Foreign body reaction and rejection	In the case that the body perceives the implanted device as a foreign item, it may respond to it as a foreign body or, in severe circumstances, reject it.	The risk of rejection can be decreased by choosing materials that minimize immunological reaction and by thoroughly evaluating biocompatibility.
Implant migrations	Over time, implants may move or migrate from their initial location, which might lead to pain, harm to nearby tissues, or compromise the BCI's functionality.	To stop migration, proper fixing methods and ongoing observation are necessary. Furthermore, continuous evaluations can spot early indications of implant displacement.
Mechanical Failure	The functionality of implants may be affected by mechanical failures such as fractures, breakage, or component disconnection.	To prevent mechanical failures, it is essential to do thorough testing on all materials and components and to continuously check the structural integrity of the device.
Long-term Biocompatibility	As the body adjusts to the implanted device over time, there's a chance that biocompatibility may decrease, and the likelihood of adverse responses will rise.	To track changes in biocompatibility and handle any new problems, long-term research and frequent patient follow-ups are required.
Chronic Exposure to Electromagnetic Fields	Implants may be subjected to electromagnetic fields, especially while using wireless communication equipment. This exposure may result in interference, heating, or unexpected consequences.	By following safety regulations and designing implants with electromagnetic compatibility in mind, the likelihood of negative long-term consequences from exposure can be decreased.

Table 2. Safety Risks of Implanted BCIs (continuation from p.88).

Category	Risks	Mitigations
Psychological and Social Impact	People who have had BCIs implanted may have psychological anguish, problems with body image, or self-perception.	To address psychological problems, comprehensive pre-implantation counseling, support networks, and regular mental health evaluations are crucial.
Privacy and Ethical	Privacy, permission, and the possible abuse of sensitive information are among the ethical issues that are brought up by the collecting and use of brain data.	To address ethical and privacy hazards, it is crucial to establish explicit ethical norms, acquire informed permission, and implement strong security measures.

Current research and technological developments try to reduce them and enhance the effectiveness and safety of implanted BCIs. It is imperative that researchers, healthcare providers, and regulatory agencies work closely together to guarantee that the advantages of implanted BCIs exceed the obstacles involved.

The possibility of unwanted access to brain data is the main source of security concerns with implanted BCIs. Ensuring the confidentiality, integrity, and privacy of neural information is essential as BCI grow increasingly sophisticated and incorporated into the human body. Table 3 shows the security challenges with possible mitigation suggestions[20].

Table 3. Security Challenges in implanted BCI (continued on p.90).

Category	Challenges	Mitigations
Unauthorized Data Access	Unauthorized access to implants that capture brain data may be possible. Hackers may be able to get private information about a person’s brain activity if it is not adequately safeguarded.	To guard against unwanted access, it is critical to use strong encryption techniques for data transit and storage. It is imperative to include access restrictions and authentication systems to guarantee that the BCI system may only be accessed by authorized users or devices.
Privacy	Neural data is extremely delicate and intimate in nature. Unauthorized access to this information may jeopardize personal privacy and give rise to moral dilemmas.	It is critical to strictly follow privacy laws and guidelines. It is important to have clear informed consent procedures in place and give people authority over who can access their brain data. User privacy can be further protected by putting anonymization techniques into practice.
Risks of Wireless communications	A lot of BCIs that have been implanted connect wirelessly to networks or other devices. This raises the possibility of data alteration by unauthorized parties during transmission, surveillance, or interception.	To reduce the dangers associated with wireless communication, it is essential to use secure communication protocols, implement robust encryption for wireless communication channels, and update security measures on a regular basis.
Manipulation of the device	Malevolent individuals may try to physically alter the implanted BCI device in order to control it improperly, send out false signals, or alter its functioning.	Secure enclosures, monitoring systems, and tamper-resistant features can all be included in the design of BCIs to help identify and stop physical tampering. Firmware upgrades and regular security checks are also crucial.

Table 3. Security Challenges in implanted BCI (continuation from p.89).

Category	Challenges	Mitigations
Cybersecurity Threats	The BCI system might be vulnerable to malware or cybersecurity assaults that damage system integrity or steal neural data if it is connected to external networks.	To guard against malware and online attacks, strong cybersecurity measures should be put in place. These include firewalls, intrusion detection systems, and frequent security audits. It is crucial to make sure the BCI system complies with accepted cybersecurity best practices.
Challenges of Authentication	It is difficult to verify the user's identification and stop illegal access to the BCI system. Strong authentication procedures are required, taking into account the distinctiveness of brain data as a factor in authentication.	You may improve the security of BCI systems by putting in place continuous authentication, biometric verification, and multi-factor authentication. It is also essential to educate users on safe procedures.
Security of data storing	It is critical to securely store neural data to avoid data breaches and illegal access. Unauthorized access or hacking into stored neural data could lead to privacy violations, exploitation, or misuse. Data storage methods (cloud vs. local) come with distinct risks. For example, cloud storage is vulnerable to remote hacking, while local storage may face risks of physical theft or damage to devices.	To safeguard the security of neural information, it is imperative to utilize robust encryption for stored data, secure storage infrastructure, and strict access controls. In cloud storage, data encryption should be end-to-end, and access should be controlled via multi-factor authentication. For local storage, devices should be physically secured, with encryption applied both at rest and during transmission. Regular security audits, compliance with data protection regulations (e.g., GDPR), and secure backup strategies should be implemented to minimize risks.
Regularity Compliance	It is critical to abide by applicable privacy and data protection laws. Noncompliance may give rise to moral and legal dilemmas.	BCI developers should be aware of and abide by all current and future laws pertaining to the handling, storing, and processing of brain data. This entails getting users' informed permission and giving them clear information about how to use and secure their data.

A multidisciplinary strategy incorporating specialists in neuroscience, cybersecurity, ethics, and regulatory compliance is necessary to address these security concerns[21]. It is imperative that researchers, developers, and regulatory agencies maintain constant communication to guarantee that implanted BCIs are not just cutting edge technologically but also safe and privacy-preserving.

CASE STUDY

RITA LEGGETT'S IMPLANTED ELECTRODE FOR EPILEPSY MANAGEMENT

A report on the case that was published in Brain Stimulation states that Rita Leggett was diagnosed with severe persistent epilepsy at the age of forty [22]. Over the years, she tried a lot of different treatments, but none of them really helped her control her disease. In this case study, Rita Leggett, a 41-year-old patient, discusses her experiences with the 2010 NeuroVista

device implantation and the difficulties she had following its removal in 2013. Rita Leggett's seizure control improved when the NeuroVista gadget was implanted. Leggett was able to proactively take clonazepam, a preventive drug, to avoid the incidence of seizures since the gadget correctly recognized imminent seizures. But the research shows that Leggett's psychological health suffered greatly when the gadget was removed in 2013 due to NeuroVista's financial difficulties. The removal went against her wishes and made her more anxious and distressed. The case study presents ethical questions about the removal of medical equipment that has worked well for certain patients, especially when the choice is influenced by outside variables like the manufacturer's financial struggles. Leggett's example highlights how crucial it is to take patient choices and any psychological fallout into account before stopping medical measures. Rita Leggett's experiences highlight the necessity for moral judgment in the realm of medical technology, guaranteeing that patients receive efficient care and that, in the event that an intervention is halted, their psychological well-being is taken into account.

SPEECH NEUROPROSTHESIS DEVELOPED FOR A 45-YEAR-OLD MAN WITH ADVANCED ALS

The patient, who suffered from tetraplegia and severe dysarthria, received an implanted BCI consisting of four microelectrode arrays placed in the left ventral precentral gyrus [23]. These arrays recorded neural activity from 256 intracortical electrodes, enabling the patient to communicate by decoding his attempted speech into text, which was then vocalized using text-to-speech software. While the device successfully restored the patient's ability to communicate, the case highlights several safety and security concerns that must be addressed to ensure the safe and ethical use of implanted BCIs. One of the primary safety concerns is the risk associated with the surgical implantation of the device. The patient underwent a 5-hour surgical procedure to implant microelectrode arrays, which carried risks such as infection, inflammation, and tissue damage. Although no serious adverse events occurred, the patient experienced transient muscle spasms and incisional pain post-surgery. These risks underscore the importance of careful surgical planning, the use of biocompatible materials, and rigorous post-operative monitoring to minimize potential complications. Overheating is another potential safety issue. Prolonged use of the BCI could cause the device to overheat, potentially damaging surrounding brain tissue. Although no overheating was reported in this case, the patient used the device for extended periods, including a continuous 7,7-hour session. Integrating thermal sensors and cooling mechanisms into the device could help mitigate this risk. In addition to safety concerns, implanted BCIs raise significant security challenges. One of the most pressing issues is data privacy. The BCI decoded the patient's neural activity into text, which was displayed on a screen and vocalized. If this data were intercepted by unauthorized parties, it could reveal sensitive information about the patient's thoughts and intentions. To protect user privacy, robust encryption and secure data transmission protocols are essential. Cybersecurity threats are another major concern. Implanted BCIs rely on external computers and software for signal processing, making them vulnerable to hacking. A cyberattack could disrupt the system or manipulate its outputs, potentially causing harm to the user. Implementing robust cybersecurity measures, such as multi-factor authentication and intrusion detection systems, is critical to prevent unauthorized access. Additionally, BCI's software could be vulnerable to malware, which could disrupt its functionality or produce incorrect outputs. Regular software updates and rigorous testing are necessary to prevent such vulnerabilities. Ethical and regulatory considerations are equally important. The patient provided informed consent for the implantation and use of the BCI but ensuring that patients fully understand the risks and benefits of such devices is crucial. Regulatory bodies must establish guidelines for the safe and ethical use of BCIs, and equitable access to this technology must be ensured to avoid exacerbating existing health disparities. In conclusion, the case of the ALS patient demonstrates the transformative potential of implanted BCIs for restoring communication in individuals with severe disabilities. However, it also highlights the importance of addressing

safety and security concerns to ensure the safe and ethical use of this technology. Surgical risks, device malfunctions, and long-term durability must be carefully managed, while robust cybersecurity measures are essential to protect neural data and prevent unauthorized access. As technology evolves, ongoing research and collaboration among engineers, medical professionals, cybersecurity experts, and policymakers will be essential to unlock the full potential of implanted BCIs while minimizing risks.

ETHICAL INVESTIGATIONS

HRI and implanted BCIs, raise a number of ethical issues that require serious thoughts [24]. The incorporation of this cutting-edge technology presents concerns about permission, privacy, autonomy, and possible societal repercussions. Table 4 shows the ethical consideration of Implanted BCI with their Balancing navigation.

The moral implications of implanted BCIs in HRI necessitate striking a careful balance between advancing technology and preserving personal autonomy and well-being. It takes an integrated group of ethicists, technologists, legislators, and the general public to appropriately

Table 4. Ethical Considerations of Implanted BCI.

Category	Issue	Balancing navigation
Informed Consent	Direct brain-to-implant interfaces are necessary for BCI implantation. Because technology is always changing and has potential long-term implications, obtaining informed permission becomes more complicated.	A strong framework is necessary to guarantee that people are fully aware of the advantages, disadvantages, and possible repercussions of BCI implants. This calls for constant learning and updating as technology develops.
Privacy & security	Since BCIs may be able to get private information straight from the brain, privacy and personal data security are at risk.	Cybersecurity, encryption, and strict laws are needed to strike a balance between the advantages of modern technology and protecting people's privacy.
Autonomy	Implantable BCIs raise questions about the notion of personal autonomy by having the ability to alter or control a person's feelings, ideas, or decision-making processes.	Setting explicit limits on the degree to which BCIs can be used to manipulate people is essential. Maintaining individual agency is crucial, and laws must forbid compulsion or manipulation.
Access	Differences in the accessibility and cost of BCI technology might result in a gap between those who can afford improvements and those who cannot.	In order to avoid societal stratification, policies addressing fair access to BCI technology are necessary. Collaboration between the public and private sectors is necessary to guarantee affordability and wide availability.
Health effect on long-term	Researchers do not completely understand how implanted BCIs will affect one's wellness in the long run. Brain interfaces could come with unanticipated hazards or repercussions.	It is crucial to prioritize safety in research and development, conduct long-term monitoring, and disclose any possible health hazards in a transparent manner. Ethics evaluations of the effects of technology on health must be conducted on a regular basis.
Social and cultural impact	Because BCIs go against established social conventions and cultural standards, there may be opposition to or prejudice against users of the technology.	Addressing cultural and societal issues can be facilitated by encouraging open discourse and including many viewpoints in the creation and application of BCIs. Building acceptance and understanding through public interaction is essential.

traverse the rapidly changing field of BCI technology. Future developments in implanted BCI technology for HRI are probably going to concentrate on capabilities enhancement, better integration, safety and security, and ethical issues. It will take ongoing study and interdisciplinary cooperation to appropriately traverse the complicated field of neurotechnology.

CONCLUSION

Over the past few decades, advancements in BCI technology have unlocked vast possibilities, creating new methods of interaction and communication between humans and robots. On the other hand, the security of implanted BCIs has become a critical concern in addition to safety concerns. Robust safeguards against unauthorized access, cyber threats, and possible misuse are necessary due to the unique risks introduced by the continuous link between the human brain and robotic devices. To strengthen the robustness of these interfaces against external threats, strict authentication procedures must be combined with the creation of secure and encrypted communication protocols. In the exciting but complex field of implanted BCIs for human-robot interaction, multidisciplinary cooperation is essential. The establishment of complete rules and standards that prioritize safety and security requires the convergence of knowledge from several domains, including neurology, robotics, cybersecurity, and medicine. Through cooperation, the dangers associated with BCIs are reduced and their advantages are optimized. Finally, the future of BCI in human-robot interaction should be not only highly developed, but also intrinsically safe and safeguarding of people's welfare.

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