Cambridge Quarterly of Healthcare Ethics (2024), 1–22
doi:10.1017/S096318012400063X

CAMBRIDGE
UNIVERSITY PRESS

RESEARCH ARTICLE

Wounds and Vulnerabilities. The Participation of Special Operations Forces in Experimental Brain–Computer Interface Research

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Abstract

Brain–computer interfaces (BCIs) exemplify a dual-use neurotechnology with significant potential in both civilian and military contexts. While BCIs hold promise for treating neurological conditions such as spinal cord injuries and amyotrophic lateral sclerosis in the future, military decisionmakers in countries such as the United States and China also see their potential to enhance combat capabilities. Some predict that U.S. Special Operations Forces (SOF) will be early adopters of BCI enhancements. This article argues for a shift in focus: the U.S. Special Operations Command (SOCOM) should pursue translational research of medical BCIs for treating severely injured or ill SOF personnel. After two decades of continuous military engagement and on-going high-risk operations, SOF personnel face unique injury patterns, both physical and psychological, which BCI technology could help address. The article identifies six key medical applications of BCIs that could benefit wounded SOF members and discusses the ethical implications of involving SOF personnel in translational research related to these applications. Ultimately, the article challenges the traditional civilian-military divide in neurotechnology, arguing that by collaborating more closely with military stakeholders, scientists can not only help individuals with medical needs, including servicemembers, but also play a role in shaping the future military applications of BCI technology.

Keywords: brain–computer interface; special operations forces; neuroethics; nanoethics; armed forces; artificial intelligence

Introduction

The term "dual-use" technology has evolved to encompass various meanings, but historically, it referred to technological applications with both civilian and military applications.[1] Brain–computer interfaces (BCIs) are a prime example of emerging dual-use neurotechnologies. While the technology has allowed a tetraplegic man to stand, walk, and even climb stairs, it has also allowed a healthy individual to control multiple drones using only their thought.[2] Although BCIs are still in the clinical stage and face significant neuroscientific and engineering challenges, the armed forces of countries such as the United States, China, and Russia view BCI technology as a promising instrument for enhancing their servicemembers' capabilities. Generally speaking, they envision neurotechnologies to enable "biotechnological interventions in the healthy body to boost a function above the statistically normal range of species-typical performance or above individual maximum capabilities, or to create novel attributes."[3]

In contrast to other military populations, U.S. Special Operations Forces (SOF) exhibit a particular openness to cutting-edge and experimental technologies, including BCIs.[4] As two officers argue, "since technology can decide the outcome on the battlefield in today's modern war, a testbed for emerging and existing technology must exist within every modern army. SOF, through its culture and small scale, has traditionally provided this testbed."[5] For 2025, U.S. Special Operations Command (SOCOM)—

responsible for organizing, training, and equipping SOF—has requested a funding increase of $1.082 million specifically "for truly disruptive technologies," which may include BCI advancements.[6] Experts working with the SOCOM community predict that SOF will become early adopters of BCI-based enhancement by 2030.[7] Given that SOF personnel operate in volatile and high-risk security contexts where conventional forces are seldom deployed, BCIs offering enhanced capabilities are expected to offer this military population significant, and potentially strategic, advantages.[8]

This article contends that, instead of waiting for BCI-based enhancement technology to mature, SOCOM should engage in on-going translational research in medical BCIs, as this technology has significant rehabilitative potential to address some of the debilitating injuries and illnesses among the SOF military population. The fallout from two decades of the global war on terror, along with continued high-risk missions and hazardous training, has led to physical and psychological challenges that some researchers have described as "operator syndrome."[9]

The current article examines SOF-specific medical conditions and explores how wounded SOF personnel and veterans could not only benefit from but also contribute to the on-going translational BCI research. More specifically, it outlines six rehabilitative BCI applications for SOF personnel. Differentiating between research conducted for the welfare of military personnel and research driven solely by the goal of military mission success, this article strongly prioritizes the former and invites a more nuanced understanding of military applications of neurotechnology, moving beyond the traditional dual-use dichotomy.[10]

This article aligns the scientific community's focus on translational research with the desire of SOF personnel to return to military service following life-altering injuries and illnesses.[11] While the former underscores the growing importance of research that bridges scientific advances and practical applications, SOF personnel consistently demonstrate a preference for returning to duty over permanent retirement, even after severe injuries.[12] For instance, Jeffery Belisle et al note that "[m]embers of the USA Special Forces (USA SF) had the highest return-to-duty rate, with 58% of amputees retained … [a] lthough USA SF soldiers had similar amputation patterns" relative to other miliary specialties.[13] This article argues that SOCOM should harness the strong commitment of injured SOF personnel to return to service. Recognizing this motivation as a valuable resource, SOCOM should explore opportunities for these personnel to participate voluntarily in translational BCI research, aligning their rehabilitative needs with emerging BCI neurotechnologies. This approach ensures that both the personal commitment of SOF members and translational BCI research are ethically integrated.

SOCOM operates under the U.S. Department of Defense (DoD), which, along with the U.S. Department of Veterans Affairs (VA), plays a critical role in advancing biomedical research to address the health needs of military personnel and veterans. The DoD and VA collectively own more than 1,000 biomedical patents, underscoring their substantial contribution to medical breakthroughs.[14] This extensive intellectual property portfolio demonstrates their capability to transition novel technologies, such as BCIs, from laboratory research to practical use. The DoD also collaborates closely with private industry to bring early-stage medical technologies to market, which is essential for translating BCI innovations into real-world medical solutions. Additionally, under a special authority granted by Congress, the DoD works with the U.S. Food and Drug Administration (FDA) to expedite the approval of drugs and medical devices for military personnel. This partnership could play a vital role in fast-tracking BCI technology for rehabilitative purposes.[15] Thus, the DoD's resources, expertise, and established partnerships make it uniquely qualified to advance translational research into medical BCI technology.

This article draws on scientific literature related to BCI technology, primarily utilizing comprehensive and narrative reviews that highlight both current achievements and challenges in BCI development. Additionally, it incorporates insights from the field of military medicine, including special operations medicine. At the intersection of these disciplines, the article also integrates perspectives from military studies and the burgeoning field of neuroethics, ensuring a realistic understanding of the demands placed on SOF personnel while carefully examining the ethically intricate nature of experimental research involving human subjects.

The article is structured into eight sections. The first three sections introduce SOF as a distinct military cohort within the U.S. Armed Forces and explore their intense training and deployment as well as the resulting injury and illness patterns that have emerged since the global war on terror. In the fourth section, BCI technology is introduced, setting the stage for the fifth section, which explores six ways in which current BCI research might aid in the rehabilitation of both physical and psychological injuries. The sixth section explores specific challenges that are equally relevant to both military and civilian applications of medical BCIs. In the seventh section, the article examines the ethical and psychological implications of wounded SOF participating in experimental BCI research, followed by a short conclusion.

U.S. SOF military populations

With a mere three percent of the entire U.S. military, SOF represents a small yet distinct subpopulation within the American armed forces.[16] At the beginning of their careers, SOF personnel are generally more psychologically resilient and under better physical condition than their conventional counterparts.[17] However, they typically undergo more intense training and face more frequent deployments, exposing them to distinct risks.[18] Compared to conventional forces, SOF personnel tend to have longer military careers (14 vs 6 years) and are more likely to deploy to combat zones (93% vs 51%).[19] Additionally, SOF units routinely operate in austere environments, where conventional forces rarely deploy. In these environments, limited or nonexistent support often results in prolonged evacuation times or a complete lack of access to medical and surgical facilities, so that SOF operators generally require significant self-sufficiency and adaptability.[20] They usually deploy in small groups, typically including one to two medics who, in emergency situations, must make critical, and daunting, decisions about the allocation of limited medical resources.[21]

SOCOM consists of approximately 70,000 personnel, including Active Duty, Reserve, National Guard, and civilian personnel assigned to its headquarters, its four components, and subunified commands.[22] SOCOM's four components include the Army Special Operations Command, the Naval Special Warfare Command, the Air Force Special Operations Command, and the Marine Corps Forces Special Operations Command.[23] U.S. Army SOF include approximately 36,000 soldiers from the Active Army, National Guard, and Army Reserve organized into Special Forces, Rangers, and special operations aviation units, along with Civil Affairs units, military information units, and special operations support units.[24] The Air Force Special Operations Command comprises approximately 17,000 active, reserve, and civilian personnel, while the Naval Special Warfare Command includes roughly 11,000 personnel, such as active-duty and reserve component Special Warfare Operators, known as the Sea, Air, Land (SEAL) teams and numerous crewmen and civilian staff.[25] The Marine Forces Special Operations Command is the youngest SOF command, established in 2005. It comprises approximately 3,500 personnel.[26] This short overview illustrates the heterogeneity of the U.S. SOF community, pointing to distinct subtypes—such as maritime SOF and enablers—each of which may have their own slightly different patterns of medical challenges.[27]

The SOF community shares certain cultural traits. A few of these defining characteristics warrant attention, as they contribute to—or may be the root cause of—some of the medical challenges. A key element of this culture is SOF's mission-first mentality. According to John Taft et al "the singular focus on accomplishing the mission even in unique and unorthodox ways—has become the core of SOF culture".[28] As a result, operators often downplay or ignore potentially serious injuries and symptoms, even at the expense of their physical and mental health.[29] SOF officer Derek Price describes it as a "show no weakness" culture.[30] SOF personnel are also generally reluctant to seek medical or psychological support due to their "desire to stay attached to and cooperative with their unit rather than being separated."[31] This mindset not only leads to the underreporting of injuries and illnesses but also encourages other maladaptive behaviors such as self-medicating and neglecting proper recovery.[32] However, failing to address even minor injuries or psychological symptoms can allow these issues to worsen, potentially resulting in debilitating conditions that not only compromise combat effectiveness but also ultimately result in medical discharge.[33]

Typical mission and training injuries

The range of SOF missions includes highly kinetic operations, such as hostage rescue, and unconventional warfare, which often involves working and living among indigenous populations in foreign countries.[34] SOF personnel routinely conduct intelligence gathering in non-permissive and semi-permissive environments, which may involve enduring extreme conditions such as physical immobilization for up to two weeks, limited nutrition and severe weather conditions.[35]

To meet the demands of such missions, SOF personnel undertake rigorous physical conditioning comparable to that of professional athletes, enabling them to maintain peak physical performance at different altitudes and in diverse environments, including deserts and polar regions.[36] Their training also includes hazardous activities such as parachuting for airborne infiltration, using explosives to breach fortified structures and carrying heavy equipment over various distances and terrains.[37] In addition, SOF personnel undergo more extensive and intensive weapons training than their conventional counterparts.[38] As they are "routinely exposed to hundreds of subclinical blast overpressures and direct impacts to the head during training," among the most common medical incidents they experience during training are traumatic brain injuries (TBIs).[39] The high prevalence of musculoskeletal injuries is another central training-related health challenge.[40]

Maritime SOF, such as the Navy SEALs, may face greater danger from explosive blasts underwater, both in training and combat. Underwater blasts propagate further than air blasts of the same force, causing pulmonary and abdominal injuries over greater distances than those experienced on land.[41] The mechanisms underlying injury from underwater explosions are less understood than land-based explosions, leaving not only the immediate but also the long-term effects on the maritime SOF population poorly understood.[42] This includes the potential for unique neurological impacts, which may add to the distinct health challenges faced by maritime SOF personnel.[43]

The occupational tasks and hazardous training activities within military populations vary significantly, leading to distinct injury patterns across different groups.[44] Some medical researchers have conceptualized SOF-related medical challenges as "operator syndrome."[45] This syndrome is understood as the cumulative impact of an exceptionally high allostatic load—the combined physiological, neural, and neuroendocrine responses to prolonged chronic stress and the extreme physical demands. Compared to conventional forces, SOF personnel also experience a greater incidence of comorbidities, including higher rates of chronic pain, osteoarthritis, and hip fractures.[46] As noted by Gloria Park et al, SOF personnel "bear unique burdens for training and deployment."[47]

SOF health problems related to GWOT, training, and missions

Historically, SOF were conceptualized as a strategic instrument, intended for missions that were too politically sensitive or otherwise complex to apply conventional forces. SOF were viewed as "a scalpel and not a chainsaw."[48] However, this changed during the global war on terror (GWOT), where the average weekly deployments of SOF rose from approximately 2,900 in 2001 to ca. 7,200 in 2014.[49] In response to the growing demand of special operators, the DoD increased their numbers. These servicemembers deployed continuously to Afghanistan, Iraq, and numerous other areas of operation such as the Philippines.[50] As one observer put it, "SOF used to be a force that is globally deployable; now we are a globally deployed force."[51] It was common for an operator with ten or more years of service to have up to fifteen deployments, each lasting several months, and to have participated in hundreds of combat missions known as "direct action."[52]

Members of the SOF community have repeatedly reflected on the "nearly two decades of shouldering a disproportionate number of combat rotations," acknowledging the profound challenges this has caused.[53] Among the most difficult and debilitating of these challenges have been the deaths of teammates, as well as other individuals.[54] One servicemember reflects: “Consciously, you understand you did the best you could for those guys, but somehow you’re very implicated in their death just by your presence, especially once human beings die in your arms in a very horrible way.”[55] Such experiences have made it harder for personnel to readjust to garrison life and reconnect with their families.[56] The psychological burden of loss, coupled with the constant transition between combat and civilian life, were compounded by political decisionmakers’ overreliance on SOF, resulting in the high deployment frequency.[57] This strain has led to a range of psychological and physical challenges, affecting the long-term wellbeing of many.[58] As one Special Forces veteran succinctly put it, “we broke a lot of people.”[59]

Particularly, during the wars in Afghanistan (Operation Enduring Freedom) and Iraq (Operation Iraqi Freedom), SOF servicemembers suffered from TBIs, along with related conditions such as depression and PTSD.[60] During the early years of GWOT, several factors, including a poor documentation of blast exposures, made the diagnosis and treatment of TBIs difficult.[61] In the combat theater, servicemembers were often sleep-deprived, under significant psychological stress and dealing with potentially traumatic experiences, all of which could easily mask TBI symptoms.[62] Furthermore, symptoms of TBIs can be delayed, subclinical, or not externally visible, further complicating diagnoses and therapeutical approaches.[63] Awareness of TBIs within the military community began to increase with the use of improvized explosive devices (IEDs) by adversary combatants during the 2000s.[64] Given SOF’s frequent exposure to IEDs, incoming rockets, mortars and other explosive weapons, TBIs have been called the “signature injury” of GWOT.[65]

TBIs are associated with physiological changes in the brain, including excessive connectivity between neural networks, a phenomenon that is under ongoing study.[66] This hyperconnectivity is believed to disrupt normal brain function by overloading communication between neurons and leading to inefficient signal processing. Recent research highlights the involvement of the thalamus and the cortex in this process.[67] The thalamus is responsible for processing and transmitting sensory information (except smell) to the cortex, where it is integrated into higher cognitive functions such as perception, decision-making and motor control.[68] Both brain regions play critical roles in regulating consciousness, behavior. and alertness. When hyperconnectivity affects these brain areas, servicemembers can experience difficulty processing sensory information, cognitive impairments, and behavioral challenges, preventing some from continuing their duties and resulting in medical discharge. According to Stephen Braden et al, only 6 percent of servicemembers who experience severe TBIs return to active service.[69]

Moreover, TBIs are linked to a range of comorbidities, including depression and posttraumatic stress disorder (PTSD). These conditions, in turn, have been associated with increased suicidal ideation and suicide.[70] In 2014, then-SOCOM commander Adm. William McRaven stated that the suicide rate among SOF personnel had reached a record high, surpassing that of other military populations.[71] He observed, “My soldiers have been fighting now for 12, 13 years in hard combat—hard combat—and anybody that has spent time in this war has been changed.”[72] This statement underscores how prolonged exposure to combat affects SOF personnel both physically and mentally. In 2017, a comprehensive suicide study concluded that SOF personnel had nearly zero risk of suicide.[73] This conclusion was starkly contradicted in 2018, when their suicide rate tripled.[74] While the suicide rate has fluctuated since, the broader issue of suicidality within the SOF community has persisted, even after the official end of GWOT in 2021.[75] The epidemiology of suicidality highlights the deep and lasting impact of the mental burdens, calling into question the long-held assumption of extraordinary SOF resilience.[76]

In addition to TBIs and the mental health struggles, SOF experienced significant musculoskeletal injuries during GWOT. Their overdeployment and insufficient recovery time resulted in physical overuse.[77] In combat theater, musculoskeletal injuries included extremity damage from penetrating, blunt, blast, and crush injuries.[78] They often led to muscle and nerve damage, resulting in loss of functionality. Katrina Hutchison and Wendy Rogers also note that “the use of IEDs in wars in Afghanistan and Iraq, with associated complex and contaminated injuries, has contributed to a new rise in amputations.”[79] In addition to IEDs, parachute insertions into combat were associated with severe musculoskeletal injuries.[80] Airborne operations, particularly landings, were the leading cause of spinal cord injuries.[81] The low rate of immediate evacuation and medical treatment following these injuries highlights the austere conditions under which SOF operate as well as the, at times problematic, prioritization of mission success over health preservation, with debilitating effects for the injured individual.[82]

Chronic pain has been one of the most common comorbidities experienced by GWOT veterans as a consequence of both musculoskeletal injuries and TBIs.[83] Medical researchers have observed higher rates of chronic pain in SOF compared to other military populations (54% vs 23%).[84] The nature of their pain varies significantly in terms of duration, frequency, location and severity. Researchers also report that SOF personnel tend to use ketamine and fentanyl more frequently than other servicemembers as part of their medical care, which raises some concerns about the risk and prevalence of drug dependence due to the (self-)medication of chronic pain.[85]

Moreover, sensory injuries have resulted in both vision and hearing impairments. Diagnosing and treating these conditions in combat zones can be particularly challenging and, in severe cases, may lead to deafness or blindness.[86] Head trauma-related eye injuries, particularly in the back of the eye, can be easily overlooked in patients with multiple traumas.[87] Even in operators who appear otherwise unharmed, the gradual degeneration of hearing may go undiagnosed and untreated until the condition has significantly progressed. The loss of hearing and vision has life-altering effects on both the military career and the overall quality of life.[88]

Traumatic brain injuries, musculoskeletal damage, chronic pain, depression, PTSD, suicide, and sensory impairments such as hearing and vision loss are key features of the "operator syndrome."[89] These conditions are not only direct consequences of the intense demands placed on SOF personnel during GWOT and current operations but also reflect the physical toll exacted by their rigorous training regimens. The cumulative impact of these injuries has forced many operators to confront a life-altering reality: transitioning from being among the military's most capable warfighters to being medically discharged and dependent on care for basic daily functions.[90] This shift not only signifies a loss of physical ability but can also lead to a sense of identity loss.[91] The individual confronts a dual burden: the physical debilitation and a psychological disorientation.[92]

BCI technology

In healthy individuals, intent is typically communicated through speech or peripheral nerves and muscles. Severely injured or ill individuals often lack these options, and BCIs offer them a new output pathway—these devices capture intent from brain activity. A typical BCI system consists of at least three components: brain signal acquisition, signal processing (which involves identifying relevant patterns in the brain activity) and an output device such as a wheelchair.

Signal acquisition can take place using noninvasive, semi-invasive or invasive techniques.[93] The most common noninvasive technique in BCI systems is electroencephalography (EEG). Typically worn as a cap on the head, EEG is used due to its practicality, portability, and ability to measure brain activity directly. Brain activity can be recorded either directly, through the electrical signals generated by neurons, or indirectly, by tracking the level of blood oxygen used by those neurons. Direct techniques such as EEG provide high temporal resolution, while indirect imaging techniques, such as functional near-infrared spectroscopy, display high spatial resolution.[94] These different techniques enable different medical applications. For instance, high temporal resolution can be valuable in predicting seizures, whereas high spatial resolution can be useful in treating mental health disorders such as depression and PTSD.

Signal acquisition can also be achieved using semi-invasive and invasive techniques. This involves surgically placing the BCI either on the brain's surface or inside brain tissue. The most common semi-invasive method is epicortical electrocorticography (ECoG), which records brain signals from the surface of the brain, beneath the skull.[95] In contrast, the invasive technique uses intracortical electrodes, which are inserted directly into the brain tissue and are able to capture activity at the level of individual neurons. Semi-invasive and invasive electrodes provide the most accurate and reliable data for BCIs, but they come with significant risks, including those associated with the surgery needed to place the devices on or in the brain.[96]

Once brain signals are recorded noninvasively, semi-invasively or invasively, the BCI identifies and extracts predefined signals, known as features. These features are then translated into commands for external effectors, such as wheelchairs or computers.[97] BCIs are connected to the external effectors through wireless technologies such as Wi-Fi or Bluetooth or via tethered connections.[98]

In addition to open-loop BCIs, which send signals to effectors, there are closed-loop (or bidirectional) BCIs. These systems provide immediate neurofeedback to the user, allowing them to modulate brain activities that typically are not under voluntary control. This feedback enables the user to actively reinforce specific neural processes and pathways, making closed-loop BCIs promising for rehabilitating stroke victims, individuals with spinal cord injuries and those suffering from neurodegenerative diseases.[99] Closed-loop BCIs leverage the principle of neural plasticity, the brain's capacity for structural and functional change, allowing undamaged brain areas to take over tasks previously carried out by injured brain regions.[100]

Since the 2000s, the development of BCIs has been intertwined with advancements in artificial intelligence (AI).[101] AI subfields such as machine learning enable the BCI to learn from previous interactions with the patient, allowing for more efficient identification and interpretation of complex brain activity.[102] Given that each individual's brain activity is unique, AI plays a central role in personalizing BCIs. Additionally, sophisticated algorithms are increasingly capable of decoding more nuanced and fine-grained brain signals, contributing to the creation of advanced prosthetics that allow increasingly natural movements.[103]

BCI technology for the sake of wounded warfighters

Operations Iraqi Freedom and Enduring Freedom introduced a significant shift in how the military approached the retention of injured personnel.[104] With advancements in medical technology, particularly in prosthetics and rehabilitative care, the loss of a limb or other severe injuries no longer necessitated automatic medical discharge. As a result, more servicemembers were able to return to their original roles or to take on new positions.[105] This trend could continue in the future with the advancement of BCI technology. It has already demonstrated potential in addressing TBIs and musculoskeletal injuries, along with their associated comorbidities.

Clinical studies have demonstrated effectiveness of BCIs in the assessment of TBI-induced damage, aiding in the diagnosis ofmild, moderate, and severe TBIs, and developing therapeutic approaches.[106] Some prognostic value has also been attributed to BCIs, as they can identify even small, incremental improvements over the months following an injury.[107] Additionally, preventive uses of BCI technology, such as arresting TBI-induced memory loss, have been proposed.[108] Overall, BCI technology shows promise in making short-and long-term impacts of TBIs more controllable and responsive to treatment.

BCI technology is also making significant strides in addressing musculoskeletal injuries that, for most of medical history, were considered incurable. For example, in 2023, a team successfully restored the communication between the brain and spinal cord using a wireless BCI system, allowing a tetraplegic individual to walk again naturally.[109] As mentioned in the introduction of the article, the 40-year-old patient received two implants, one in the brain and the other on the spinal cord, which allowed him to stand, walk, and climb stairs.[110] While it is important to acknowledge challenges, such as the temporal mismatch between the patient's intention and the corresponding movements, the case demonstrates the potential for some spinal cord injuries to become less debilitating in the future, allowing SOF personnel to continue service should they choose to.

Other rehabilitative approaches include exoskeletons for tetraplegic patients. A proof-of-concept study demonstrated the successful activation of a four-limb neuroprosthetic exoskeleton over a 24-month period, highlighting another way in which BCI technology can help restore mobility and function in individuals with severe motor impairments.[111]

Closed-loop BCI technology also holds promise for SOF personnel suffering from chronic pain.[112] BCI-based neuromodulation has emerged as a potential treatment for chronic pain, offering relief without the systemic side effects of medications such as opioids.[113] Researchers are developing therapies that allow patients to directly control their brain activity via the BCI, allowing them to modulate and alleviate their pain. For instance, recent studies have shown that patients with persistent neuropathic pain following cervical spinal cord injury and chronic upper extremity pain were able to reduce their discomfort.[114] While these findings are promising, further research is needed to confirm the long-term efficacy and scalability of these approaches.

The closed-loop BCI has also shown promise in addressing traumatic experiences and mood disorders including depression.[115] In one study, researchers first identified specific biomarkers of depression and potential treatment sites by observing deep brain signals. Then they developed a closed-loop invasive BCI system, which successfully regulated these biomarkers throughout the study. As a result, the severe symptoms were alleviated during the one-year treatment period.[116] The development of closed-loop invasive BCIs is likely to become a leading research direction for treating certain neuropsychiatric disorders.[117]

BCI-based neuroprosthetics is another subfield of BCI technology with significant military relevance.[118] According to Sharlene Flesher et al, improved functioning of prosthetic arms and hands is among the most desired advancements for Americans living with severe disabilities, highlighting the urgent need for further innovation.[119] In 2004, the BrainGate team—consisting of neurologists, neuroscientists, clinicians, engineers, computer scientists, neurosurgeons, mathematicians, and other researchers from U.S. universities and institutions—achieved a breakthrough by implanting a BCI in a patient with tetraplegia, allowing them to control a multi-joint robotic arm and a prosthetic hand.[120] Since then, BrainGate has consistently conducted clinical trials with 16 BCI-implanted subjects between 2004 and 2023, giving the interdisciplinary team the largest total number of participants to date.[121] The Defense Advanced Research Projects Agency (DARPA), an agency of the DoD, contributed funding during BrainGate's early stages and currently the Department of Veterans Affairs supports individual BrainGate projects.[122]

A BCI can assist individuals with arm and hand prostheses by, for example, accurately identifying their intention to raise the artificial limb and carefully grasp an object, such as a bar of chocolate. In the early 2010s, DARPA funded a project that enabled a quadriplegic woman to do exactly this, without external assistance.[123] This example highlights a crucial capability of BCI-based prosthetics: They increasingly allow individuals to perform fine motor movements and control grip strength, both of which are essential for most daily activities.[124] Equally import, BCI technology has enabled users to feel light pressure and touch through the prosthetic, making the experience increasingly similar to using a natural limb.[125]

The field of sensory BCIs is also highly relevant to injured SOF. While cochlear implants are currently the most common type of sensory implant, research is carried out to advance BCI-based retinal implants.[126] Some retinal prostheses have matured to the point of regulatory approval.[127] These artificial retinas carry out advanced and complex image processing, providing the brain with visual data and holding significant promise for blind individuals.[128] Another promising area of sensory BCIs is somatosensory restoration, which focuses on enabling tactile sensation in previously insensate areas, a potentially transformative advancement for paralyzed individuals seeking to regain sensory feedback throughout the body.[129]

Current BCI challenges

The widespread use of medical BCI technology is currently unfeasible due to its developmental immaturity. Numerous challenges still need to be overcome, and this section focuses on three key areas: security, safety and standardization. A short examination of standardization issues highlights the technology's nascent state in an illustrative and accessible way while also underscoring the need for robust safety and security frameworks. SOF volunteers could contribute to all three of these key areas. The SOF community, known for its high-risk tolerance and ability to operate under uncertainty, may approach BCI safety and security requirements with a distinctive mindset. Their experience in confronting and successfully managing high stakes and unpredictable situations can equip them to identify potential risks or vulnerabilities that others might overlook, offering valuable insights for developing safer, more resilient, and standardized BCI systems.

One of the most commonly discussed security challenges is the risk of hacking BCIs, which rely on wireless connections and Internet connectivity. In January 2024, Elon Musk's company Neuralink reported the successful implantation of a BCI in a patient, enabling them to browse the Internet.[130] For tetraplegic patients, this capability can be transformative, offering a vital means of interaction with their environment and enhancing their autonomy. However, this also introduces the potential for malicious actors to hack BCIs, leading to the loss of patient privacy and potential manipulation of the device. The latter scenario can be considered particularly dangerous since it can cause physical harm to the user.[131] Although no incidents of so-called "brainjacking"—where an unauthorized actor hijacks a BCI device for malicious purposes—have been reported to date, researchers have successfully demonstrated the feasibility of such attacks.[132] They underscore the critical need for high security standards. To mitigate the risks, researchers are developing cybersecurity strategies for BCIs, including advanced encryption and user authentication systems.[133] Other approaches from the field of cyberbiosecurity can also contribute to make BCI technology more resilient against evolving security threats.[134]

Current BCI-related safety challenges include short-term problems, such as complications related to the implantation of the BCI, and mid-term concerns, such as the implant's biocompatibility.[135] The insertion of an electrode array into the brain can trigger an inflammatory response and lead immune cells such as the microglia to engulf (phagocytose) the implant, which may compromise its functionality.[136] Proposed solutions to the biocompatibility issue include the development of nano-sized implants, which are designed to minimize immune responses, and bioactive coatings that facilitate safer integration with host tissue.[137]

The long-term safety of both invasive and noninvasive BCIs on the patient's neurophysiology also receives attention.[138] Since closed-loop BCIs interact with neural biochemical processes, they may influence cognitive functions and behavior—raising concerns about the potential impact on an individual's bodily integrity.[139] Researchers have suggested to address these concerns by developing "a more sophisticated understanding of how identity can be affected by BCI research as well as develop ways of measuring changes in identity and interrelated aspects of the self (autonomy, authenticity, sense of agency and responsibility)."[140] However, specific strategies and instruments for mitigating these risks remain underdeveloped and necessitate further research.

Another key long-term safety challenge is the durability of invasive BCIs, as the implants are susceptible to corrosion from prolonged exposure to cerebrospinal fluid.[141] Additionally, micromovements caused by respiratory and cardiovascular functions can lead to slight shifts of the device, compromising its long-term performance.[142] Despite these obstacles, there have been notable successes. One example is a subject with tetraplegia following a stroke, who retained some control over a prosthetic arm five years after receiving the implant.[143] On average, implanted devices remain functional for 872 days, as reported by BrainGate researchers.[144]

The BrainGate team offers early yet valuable insights into the safety of BCIs. Their projects have accumulated 12,203 days of safety experience and reported 68 device-related adverse events, including 6 device-related serious adverse events.[145] However, there were no safety incidents requiring device explantation, no unanticipated adverse events, no intracranial infections, no adverse events leading to permanently increased disability related to the implanted device, and, most importantly, no participant deaths. The development of registries to collect such safety data would be particularly valuable given the wide variety of BCI hardware types, neural implant locations, targeted conditions, and demographic factors involved in BCI research.

Current BCI research remains highly fragmented, resembling a mosaic of isolated efforts rather than a cohesive and unified field. This fragmentation is largely due to the wide range of actors involved in BCI development, including startups, established companies and academic institutions, many operating with their own objectives and methods.[146] As a result, there is a lack of standardized protocols in critical areas, such as performance assessment, sensor technology, and algorithm evaluation. This lack of consistency is currently making the large-scale deployment of BCI technology unfeasible, particularly for critical applications like those involving wounded military personnel and veterans.[147]

While researchers and working groups have acknowledged the need for standardization, progress has been slow. For example, the Institute of Electrical and Electronics Engineers (IEEE) Standards Association—an organization that develops global standards for biomedical and healthcare technologies—has yet to establish fully unified protocols specifically for BCIs that can be widely adopted across the industry. Although some progress has been made, such as the IEEE P2731 initiative to unify BCI terminology, a comprehensive set of standards remains elusive.[148] One proposed approach involves adapting safety and performance standards from established fields, such as cardiac pacemakers and defibrillators, though this solution has yet to be fully implemented or proven effective.[149]

The lack of a more standardized and systematic approach to BCI research should not lead to undervaluing the importance of clinical trials—particularly since these trials are critical to advancing the field in several ways. Trials generate comparable and consistent data, validate specific algorithms, sensors and other hardware, and establish performance and safety benchmarks. Additionally, they can encourage shared goals and methodologies between researchers and developers, thereby helping to facilitate interdisciplinary collaboration. However, as important as conducting clinical trials is, equal priority must be given to developing methods for cataloguing, categorizing, and otherwise systematizing trial data. This can help to advance BCI research beyond the sum of individual translational studies.

Psychological and ethical considerations

Involvement in SOCOM-supported BCI trials could have a salutary effect on gravely wounded SOF personnel, extending beyond the immediate benefits of treatment or the assistive capabilities of BCI-based devices. By participating in these studies, wounded operators could retain an active role within the SOF community, fostering a renewed sense of purpose: Because the BCI technology that would aid wounded personnel today could eventually protect or medically assist SOF personnel in the future, those participating in BCI trials would become pioneers of significant innovation. As Johannes Kögel and Gregor Wolbring conclude, following interviews with BCI users, having a task that contributes to scientific and technological progress fosters pride, self-esteem, and social recognition, enabling individuals to maintain meaningful ways of self-identification and contribution to the SOF community.[150]

Amputees and other severely impaired SOF personnel and veterans often compare their current situation with their former abilities. One SOF veteran explains, "I was a combat helicopter pilot, top of my field, endurance for days, spoke several languages. Now, trying to problem solve, I just get exhausted, and I feel overwhelmed."[151] The profound sense of loss and negative self-perception could be alleviated through participation in SOF-related BCI trials. Involvement in translational research holds significance for patients beyond the military: as volunteers, wounded warfighters could contribute to innovations benefiting society, giving them an even stronger sense of mission and meaning.[152]

Researchers who interviewed BCI volunteers report feelings of empowerment and improved self-esteem among participants.[153] One notable study followed a volunteer for six years whose BCI implant could predict epileptic seizures and informed the patient in advance. Diagnosed with severe chronic epilepsy at the age of three, this patient had endured a lifetime of treatments, none of which successfully managed her condition.[154] The experimental BCI provided a transformative effect on her quality of life. According to Frederic Gilbert, Marcello Ienca and Mark Cook, the patient reflected: "I felt like I could do anything … I could drive, I could see people, I was more capable of making good decisions-not bad decisions."[155] The device, despite its life-changing impact, was eventually explanted because the company developing it faced financial difficulties and was forced to terminate the trial. The patient expressed profound feelings of loss, stating: "To finally switch off my device was the beginning of a mourning period for me. A loss, a feeling like I'd lost something precious and dear to me, that could never be replaced: It was a part of me."[156] This case study illustrates that BCI implants may not only facilitate a connection between brain tissue and technology but foster a deeper, more transformative relationship. The subject's connection with the device extended beyond treatment, creating what the researchers describe as a "human-machine symbiosis."[157] "Symbiosis" typically refers to relationships between living organisms. Here, cyberization may be the more appropriate term, underlining the profound reinterpretation of identity, during which the technological device becomes embedded in the individual's sense of self.[158] This process, while psychologically explainable, has ontological ramifications for the individual because they stop to perceive themselves in terms of boundaries between what is human and what is technology.

This phenomenon raises critical ethical considerations, particularly for translational BCI research, which has generally been limited in duration. SOCOM would have to acknowledge the potential psychological implications of cyberization and ensure that participants are fully informed about the likelihood of forming an ontological bond with the device. It is equally important to ensure the support necessary to manage the emotional and identity-related distress that may follow explantation, since the removal of the device could be perceived as yet another profound personal loss for a wounded servicemember. Scholars have suggested that the psychological distress following device explantation "may in some cases be directly proportional to the effectiveness of the technology," as illustrated by the epileptic patient above.[159] This insight could serve as a valuable reference point, enabling more strategic psychological and medical support for personnel postexplantation.

To preserve an injured warfighter's sense of purpose and gravitas, it is essential that they do not feel "as if they are mere tools, mere instruments, but are being treated with dignity and respect."[160] While injured SOF personnel may voluntarily consent to participate in BCI trials, they could perceive BCI-based rehabilitative research not as a genuine choice but as their final hope to reclaim some of the abilities they have lost. This sense of desperation can skew their judgment, leading them to downplay or even dismiss the significant risks posed by experimental BCI technology. Additionally, severely wounded SOF personnel are likely to have already undergone numerous therapeutic interventions and made profound adjustments to their daily life before the enrolment in a clinical trial. Disheartening and painful experiences with conventional medical treatments could contribute to the development of unrealistically high expectations regarding BCIs as "breakthrough" or "revolutionary" technology. Managing these expectations is a well-documented challenge in the BCI literature, as the "[p]hysical and emotional investment on the part of subjects is substantial."[161] Wounded individuals might hope that the device will restore their former abilities when in reality BCIs can only address specific impairments and cannot reverse all the effects of their injuries, let alone return them to their preinjury state. This potential gap between expectation and reality highlights the critical importance of ensuring that SOF volunteers understand the possibilities, limitations, and risks of BCI technology. Informed consent must go beyond technical details, addressing the psychological factors that could shape unrealistic hopes, to safeguard ethical standards in these trials.

SOCOM must address these crucial topics and ensure in-depth communication about the potential risks, side effects and uncertainties. This duty of care aligns with the broader ethical commitment of the DoD, which—as SOF personnel emphasize—has "a sacred duty to safeguard the health of those willing to serve, especially those wounded in combat or injured in training."[162] The protective frameworks are outlined in the DoD Instruction 3216.02, "Protection of Human Subjects and Adherence to Ethical Standards in DoD-Conducted and Supported Research."[163] Additionally, military personnel are generally protected by the Common Rule, established in 1991, which defines mechanisms to protect research subjects.[164] However, ensuring informed consent in BCI trials requires more than regulatory compliance. It demands innovative approaches to help volunteers grasp the profound personal implications of BCI technology. Eran Klein and Jeffrey Ojemann recommend "imaginative exercises" that prompt volunteers to reflect on how controlling a BCI might reshape their lives and identities.[165] For example, volunteers should be encouraged to imagine whether new forms of controlling the body would always be empowering or at times also disconcerting.[166] These imaginative reflections should not be one-off exercises but part of a continuous, iterative process, allowing participants to revisit and refine their understanding. Additionally, Klein and Ojemann propose a multi-session approach to present highly technical BCI-related information through multiple modalities.[167] This multifaceted approach would provide SOF personnel with repeated opportunities to ask questions, engage in critical reflection and develop a deeper, more nuanced understanding of BCIs, ultimately fostering a more robust and ethically sound process of voluntary consent.

Participants in BCI trials typically spend two to four sessions per week, with each lasting 3–4 hours, engaging in tasks related to data collection and analysis.[168] Over the course of a year, assuming volunteers participate for 40 weeks with three 4-hour sessions per week, they will have actively contributed 480 hours to research.[169] This is just one way to conceptualize the significant commitment of trial participants, which raises important ethical questions. For instance, would volunteers have the option to continue using the BCI after the study concludes, particularly if they return to military service in a new capacity? If so, who would be responsible for their medical care as BCI users?[170] Who would cover the costs of this care? Furthermore, who would ensure software updates, or monitor and resolve any malfunctions? SOCOM would have to address these critical considerations from the outset of any translational BCI research initiative, rather than delaying them until enhancement-focused BCIs are developed. This is especially important given the First SOF Truth: "Humans are more important than hardware."[171] SOF personnel emphasize that this principle reflects the community's highest priority—safeguarding the wellbeing of its people and maintaining strong relationships.[172] In the context of translational BCI research, the truth aligns closely with another cultural hallmark of SOF, namely the community's commitment to innovation, expressed in the adage "Innovate or die."[173] Adopting BCIs through the rehabilitative approach promises both: prioritizing the needs of wounded servicemembers and veterans while pioneering cutting-edge technology.

Conclusion

After decades of relying on animal studies, the transition to human trials in the 1990s marked a pivotal step in the development of medical BCIs.[174] With an increasing number of stakeholders and funding sources becoming involved in this technology, clinical trials are becoming more numerous.[175] This article has argued in favor of SOCOM's commitment to translational BCI research, enabling severely injured SOF personnel to benefit from ongoing advances in this technology, should they wish to. SOF personnel experience injury patterns that typically—although not exclusively—include TBIs, musculoskeletal injuries, depression, PTSD, chronic pain, and sensory impairments (eye and ear injuries). These conditions have been caused not only by the two-decade-long GWOT but also by current training and operations. Various applications of BCI—such as closedloop and openloop—hold the potential to alleviate these conditions and improve the quality of life for those affected.

Gaining initial insights into BCI technology through the experiences of wounded and vulnerable personnel could foster a more nuanced understanding of BCI applications among SOCOM personnel—one that moves beyond a focus solely set on enhancement. By prioritizing the immediate therapeutic benefits and addressing the practical challenges of BCI technology for injured personnel, SOCOM could cultivate a more comprehensive and ethically informed approach. This holistic understanding would not only improve the quality of life for affected soldiers but also help SOCOM better anticipate the broader implications of BCI technology. In the best-case scenario, engaging with BCI devices in their experimental stages could lead to a more responsible and ethically grounded application of BCI devices in the future.

To effectively contribute to clinical research, SOCOM would need to establish close collaborations with medical research teams. However, many researchers are hesitant to cooperate with the military due to concerns about the dual-use nature of BCI technology. Originally, dual use referred to technologies that could serve both civilian and military purposes. However, its modern interpretation, as defined by the World Health Organization, suggests that research intended to benefit society can easily be misapplied to cause harm.[176] Ethical concerns about the military use of advanced technologies such as BCIs often arise from this dual-use framework, which tends to frame military applications as inherently unethical and harmful.[177] As this article suggests, this dual-use perspective oversimplifies the ethical landscape and restricts the scope of ethical inquiry.[178] Such a narrow interpretation neglects the broader potential of BCI technology to improve the well-being and protect the lives of injured and vulnerable servicemembers. This paper invites a more nuanced approach which recognizes that responsible military applications of BCI technology, particularly in medicine and rehabilitation, can coexist with ethical research goals, benefiting both the scientific and military communities and, ultimately, society at large.

Competing interest. The author declares none.

Notes

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Cite this article: Gielas AM (2024). Wounds and Vulnerabilities. The Participation of Special Operations Forces in Experimental Brain–Computer Interface Research. *Cambridge Quarterly of Healthcare Ethics*: 1–22, doi:10.1017/S096318012400063X