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REVIEW

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A review of human augmentation and individual combat capability: focusing on MEMS-based neurotechnology

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Abstract

The purpose of this paper is to identify the relationship between human augmentation and personal combat ability improvement that overcomes physical and mental limitations according to the convergence of advanced science and technology such as biotechnology, brain engineering, and mems-based technology. We will first explain the background of the emergence of human augmentation and derive the characteristics of human enhancement through conceptual analysis of the correlation of human augmentation and cognitive abilities, which hold importance for future warfare. Afterward, through the development of brain engineering, we will present areas where advanced science and technology can contribute to improving military combat capabilities, such as cognitive abilities, decision-making abilities, situation recognition abilities, and brain stimulation. Finally, we will review the MEMS-based neural interface systems for the enhancement of human augmentation and individual combat ability.

Keywords Human augmentation, Brain stimulation, Neurotechnology, Cognitive warfare, MEMS

Introduction

The development of cutting-edge science and technology, including artificial intelligence, semiconductors, and BCI (Brain Computer Interface) technology, is presenting various concepts for future weapon systems in the defense sector. Ongoing efforts, such as the continuous pursuit of initiatives like the Army TIGER 4.0 system by South Korea that aims for ultra-connectivity and ultra-speed, reflect the application of such technologies [1]. Especially, as the importance of the cognitive domain is emphasized in future warfare, enhancing individual combat capabilities through human augmentation, and overcoming physical and mental limits, is becoming a key factor in the global technological power competition.

Human augmentation technology, as a core technology opening the era of Augmented Humanity in the twenty-first century, integrates various heterogeneous technologies such as artificial intelligence, bioengineering, semiconductors, information and communication technology, and MEMS-based BCItechnology. As shown in Table 1 below, globally, it plays a crucial role as a promising solution for future growth drivers and solutions for societal issues, under active government support. China, in particular, focuses on securing basic scientific capabilities in neuroscience and developing technological platforms to ensure national leadership in intelligence competition. China actively promotes the utilization of human augmentation technology, particularly through BCI, to prioritize competitiveness and social control. This approach fosters an intelligence-oriented military geared towards unrestricted warfare. In conclusion, human augmentation technology is expected to play a

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Table 1 Technology trends for human augmentation

Classification	The key policies related to Human Augmentation	Direction of Advancement
South Korea [2–4]	Science and Technology Future Strategy 2045 Development of Human Augmentation Suits Development of VR-Based Psychological Therapy Technology	Digital-Based Social Issue Resolution
USA [5]	Development of AI-Based Intelligent Semiconductors Technology Development based on Big Data and VR	Human Augmentation Centered around AI and Robotics
China [6]	China Brain Project Three-Year Action Plan for Advancing Next-Generation Artificial Intelligence Development of Artificial Synapse Emulation	Human Augmentation Centered on Brain Research
Japan [7]	Brain Minds Development of Wearable Suit Technology Development for Identifying Objects in Dreams through Brain Signal Analysis	Human Augmentation Centered on Robots and Machines

game-changing role in transforming the paradigm of future society. Considering the global trend focusing on artificial intelligence, robotics, and BCI technology, it is anticipated that augmentation of brain capabilities will extend to enhancing physical and social abilities. In other words, implanting chips in the brain to stimulate specific areas is thought to enhance decision-making, situational awareness, as well as overall physical and cognitive capabilities, which are essential for soldiers in combat. In this study, we aim to thoroughly analyze the concepts of human augmentation and the latest technologies related to neural engineering discussed thus far. Based on this analysis, we intend to propose ways in which the development of neural engineering can be applied to enhance individual combat capabilities in the future battlefield environment. Additionally, we seek to discuss the direction of development in the defense field. The structure of this paper is as follows: In Chapter 2, we examine the concepts and background of human augmentation, and review the current state of development in neural engineering. Chapter 3 analyzes how the progress of MEMS-based neurotechnology can contribute to enhancing combat capabilities, and Chapter 4 addresses ethical issues and remaining problems related to human augmentation. We conclude by discussing future research directions in conjunction with our findings.

Concept and background of human augmentation

Concept and domain of human augmentation

Human augmentation, first mentioned in the "Converging Technologies for Improving Human Performance (NBIC)" published by the U.S. National Science Foundation (NSF) in 2002, refers to the proactive enhancement of human physical, cognitive, and social capabilities through the convergence of various technologies such as neuroscience, artificial intelligence, information and communication technology, and biotechnology [8]. In summary, it encompasses the perception of humans as a unified platform and the technological evolution of humans to enhance physical, cognitive, and social abilities. As illustrated in Fig. 1 below, human augmentation is broadly categorized into three main domains. The first domain focuses on physical human augmentation, enhancing hardware-based physical abilities such as vision, hearing, strength, agility, speed, and endurance. Technologies like strength-enhancing robotics, 3D printing, and sensory technologies play a crucial role, and wearable suits designed for rehabilitation and tasks involving repetitive motions, prone to injuries, can also be utilized for the enhancement of combat capabilities. The second domain is cognitive human augmentation, which involves the enhancement of brain capabilities related to thinking, decision-making, perception, understanding, and problem-solving. Advances in neural engineering can enable improvements in memory, situational awareness, and decision-making abilities. In a military context, monitoring brain signals and physiological

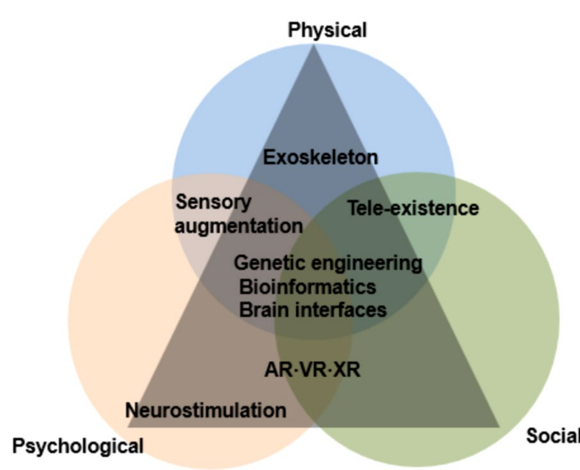

Fig. 1 Human Augmentation Technologies and the Human Platform

signals can enhance the survival and recovery abilities of combatants. Key technologies include brain stimulation, brain chip technology, Brain-Machine Interface (BCI), biochips, and sensor technologies. The third domain pertains to social human augmentation, which emphasizes communication skills, cooperation, trust, cohesion, and other essential attributes for societal participation. This augmentation of social capabilities can harness emotional information such as facial expressions, voice, and imagery to discern emotional states, thereby preventing and treating conditions like depression and panic disorders. Traditional therapeutic approaches involve physicians prescribing treatments based on patients' symptoms and test results. In contrast, treatments leveraging emotional capabilities are characterized by the potential for low-cost, personalized therapy powered by artificial intelligence, facilitated through the development and standardization of extensive databases. Key technologies in this domain include AI-driven biometric, image, and voice recognition and analysis, as well as digital therapeutics employing biomarkers.

The development of the Fourth Industrial Revolution and advancements in neural engineering

Since Klaus Schwab declared the era of the Fourth Industrial Revolution at the World Economic Forum in January 2016, it has been a prevailing opinion that nations actively embracing rapidly changing advanced sciences and technologies, such as artificial intelligence, robotics, and biotechnology, tailored to their circumstances, will evolve into leading countries globally [9]. Militarily, the effective utilization of these key technologies in combat has become a central focus for each nation. In the future battlefield characterized by hyper-connectivity, superintelligence, and super-convergence, the autonomy of systems that integrate various data in real-time and facilitate timely decision-making in response to battlefield situations is considered a crucial factor in determining victory [10]. The brain signals, as illustrated in Fig. 2, consist of action potentials forming a continuous spike train. It is observed that information is transmitted as the frequency of spike occurrences changes in response to external stimuli. Analyzing the neural circuits formed by activated neurons connected to action terminals allows the study of brain function. With the recent advancement of MEMS technology, neural probes have been developed to simultaneously measure signals from various regions of the brain, which is intricately composed of around 80 billion neurons. Particularly, the development of brain chips enables real-time simultaneous measurement of various types of brain signals such as electro-physiological signals and neurotransmitters. This technology has made it possible to identify substances causing brain disorders such as depression and Parkinson's disease [11]. Additionally, as shown in Fig. 3, the use of brain-implanted brain chips allows the monitoring of brain activity. Through this, technologies have been developed to understand the mechanisms related to neurological disorders, delivering drugs to the brain, and applying various stimuli to control animal behavior [12]. Neuralink, led by Tesla founder Elon Musk, is conducting research to enhance human brain capabilities using brain chips, aiming to control brain functions and connect to the Internet of Things, enabling activities like using smartphones through thought alone. They are advancing beyond traditional BCI technology and have completed animal experiments on pigs and monkeys. Furthermore, experiments are in progress to overcome visual impairment through visual implants by stimulating the optic nerve, with clinical trials involving humans having received approval from the U.S. FDA [13]. However, the human brain, being the most complex organ in the human body, faces significant constraints for direct use due to genetic variability, ethical concerns, and other factors. For these reasons, recent global research has been focused on brain organoids, a brain mimicry model. Brain organoids utilize the spontaneous division and differentiation of induced pluripotent stem cells to

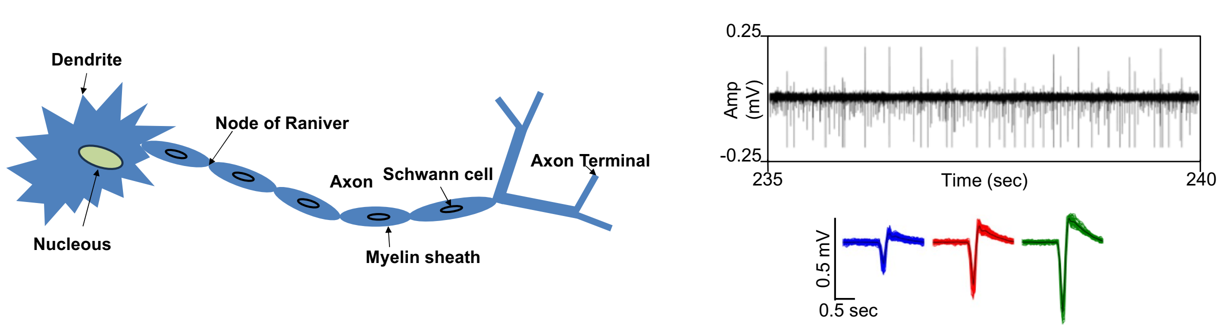

Fig. 2 The structure of nerve cells and neural signal

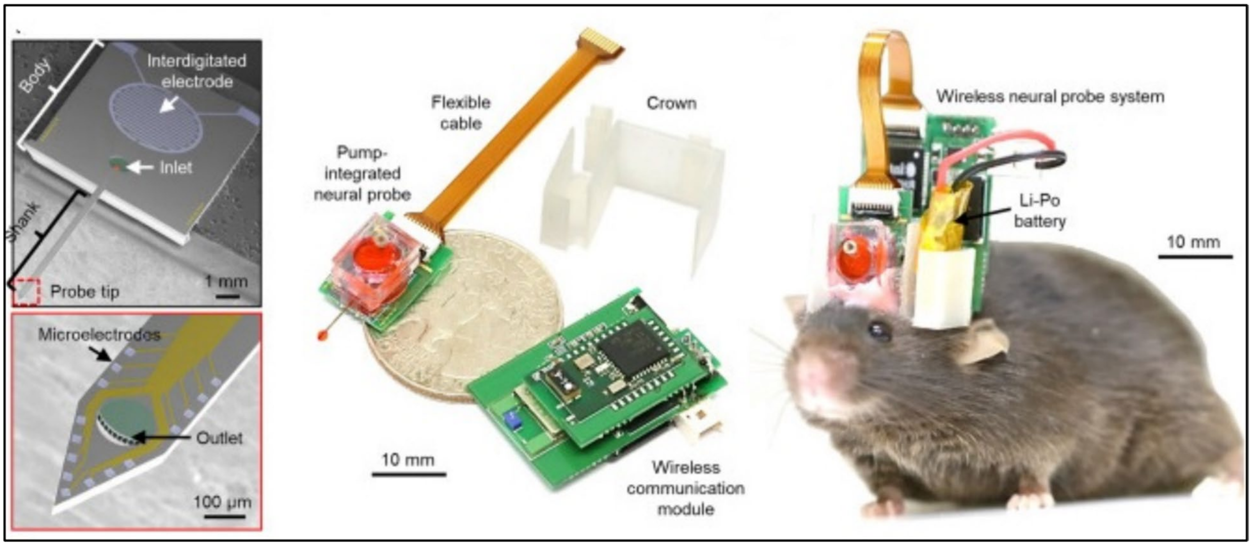

Fig. 3 Photograph showing the wireless neural probe system mounted on the head of a mouse. (reprinted from Nature Communications, Copyright (2022), with permission from Nature Communications)

form various structures resembling human brains both in shape and function. In the field of neuroscience, they are employed to model neurodegenerative brain diseases like Alzheimer's and develop treatments for such conditions [14]. Brain organoids are also utilized as platforms to implement brain tissue chips, conducting research on processes occurring in the human brain, such as development and the onset of diseases [15]. In recent studies, researchers have successfully reproduced human spinal cord tissue as a spinal cord organoid. This advancement allows for the modeling of the development of the human spinal cord and diseases related to neural tube defects. If methods for analyzing and controlling cognitive mechanisms are developed using brain mimics (Fig. 4), it may enable the control of computers and robots through biological signals, potentially leading to the development of artificial intelligence robots surpassing human-level capabilities [16].

Fig. 4 The Cognitive domain is a new space of competition (reprinted from NATO Innovation Hub, Copyright (2021), with permission from NATO)

Human augmentation and cognitive warfare

In future warfare, the core lies in who achieves cognitive dominance first [17]. This means that in future warfare, the integration of human cognitive abilities with artificial intelligence in computers, facilitated through a hyperconnected network, is crucial for achieving cognitive-behavioral processes that are faster and qualitatively superior. Cognitive warfare involves controlling the human brain to enhance cognitive abilities, manipulate aspects such as situational awareness and decision-making systems, and even advance physical capabilities by stimulating areas of the brain [18]. Augmented warriors, based on advanced science and technology, can leverage cloud-based big data and real-time analytical processing speeds for enhanced capabilities. Through platforms like social media, they can influence the cognitive mechanisms of the public. Moreover, they can impact the opponent's brain-mind, brain-neurology, and brain-psychology, influencing the outcome on the battlefield.

Advances in brain engineering and improvement of military combat power

We have previously explored the concept, background, areas, and attributes of human augmentation. The advancement of neural engineering and the enhancement of combat capabilities have led to improvements in cognitive abilities, contributing to enhanced combat effectiveness. As shown in Fig. 5, the Cognitive Technology Threat Warning System (CT2WS), conducted by the U.S. Defense Advanced Research Projects Agency (DARPA), detects and monitors brain signals to warn soldiers of potential enemy threats, thereby reducing the loss of combat effectiveness by alerting them to situations where they may be at risk [19]. Additionally, the U.S. Army's Augmented Cognition Program, conducted by Honeywell, utilizes portable sensors to monitor soldiers' electrocardiograms and electroencephalograms during mission execution, enabling agile responses to rapidly changing tactical situations on the battlefield [20]. In the near future of warfare, the pursuit of BCI is aimed at enabling Human–Machine Teams to share the battlefield environment through the assistance of artificial intelligence, facilitating timely decision-making. The advancement of neural engineering has significantly enhanced the speed of processing accurate information and rational decision-making, key components of the OODA loop, while reducing cognitive load. Consequently, this development has improved the ability to identify errors in decision-making. The progression of such technology allows not only individual decision-making but also real-time group or collaborative decision-making. This, in turn, contributes to the development of collaborative collective intelligence, exhibiting increased accuracy, a faster tempo of decision-making, and lower error rates in goal identification and image recognition. The enhancement of cognitive abilities in cognitive warfare enables precise judgment, prevents disruptions in friendly forces' hyper-connectivity, and defends against cognitive attacks by adversaries, ultimately leading to improved combat effectiveness [21]

Improve memory, concentration, and situational awareness

Brain signals measured from the human scalp are electrical signals that indirectly measure the electrical activity of the neurons comprising the brain through electrodes on the scalp. These signals exhibit amplitudes of approximately 10 to 100 μV and a frequency spectrum of 0 to 50 Hz, depending on the brain's activity states. They are categorized into invasive and non-invasive methods based on whether the skull is removed. Additionally, the brain's cortex is divided into frontal, parietal, temporal, and occipital lobes, with specific functions assigned to each region. The frontal lobe is responsible for decision-making, the parietal lobe for the body, the occipital lobe for vision, and the temporal lobe for hearing. Recent research results show that non-invasive brain modulation technologies, such as Transcranial Magnetic

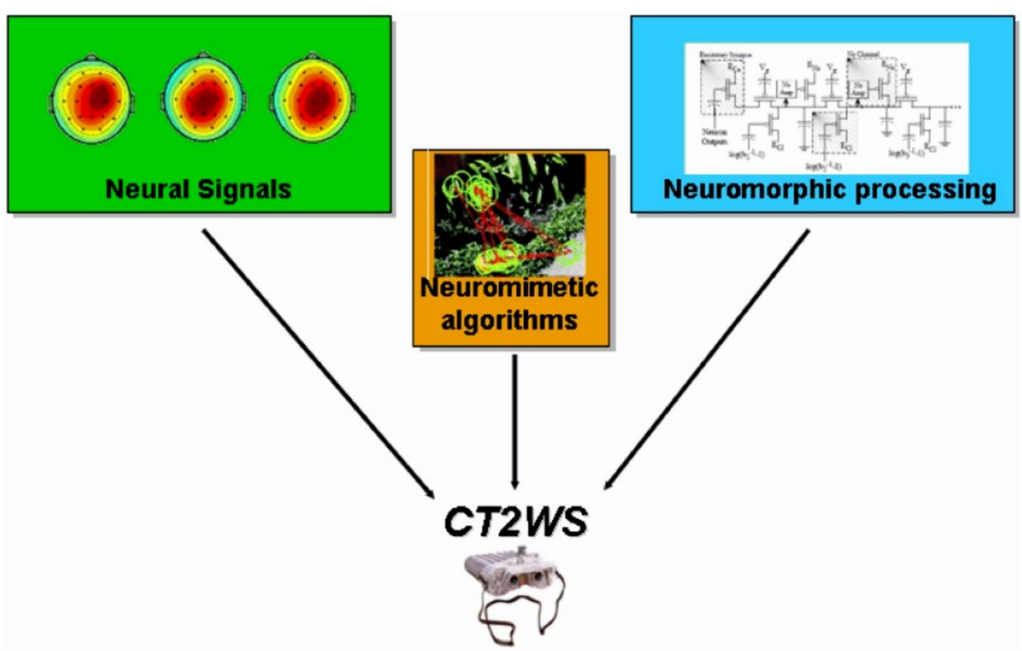

Fig. 5 Cognitive Technology Threat Warning System (reprinted from DARPA Science office, Copyright (2007), with permission from DARPA)

Stimulation (TMS) and Transcranial Current Stimulation (tCS), which use magnetic fields and currents to electrically stimulate the frontal lobe, induce synaptic plasticity and enhance short- and long-term memory and learning abilities [22]. The improvement in cognitive performance and capacity resulting from these technologies has led to increased momentary memory capacity and enhanced work efficiency, especially in situations with added cognitive load or requiring high concentration. This performance holds potential applications for combatants in uncertain battlefield environments, contributing to improved marksmanship in rifle shooting and enhancing efficiency in tasks such as precision shooting missions for combat pilots and drone operators. Enhanced cognitive abilities also contribute to improved situational awareness, a crucial factor in complex and diverse environments, including military decision-making, air traffic control, and emergency situation declarations. Situation awareness involves the perception of elements or clues within the environment, understanding and integrating perceived information within a specific context, and interpreting or predicting events in future situations. Real-time monitoring of signals from the frontal and parietal lobes has enhanced situational awareness by improving cognitive uncertainty in various contexts. Moreover, cognitive augmentation through brain stimulation enhances memory and concentration, improving learning or task performance. It assists in handling complex plans involving innovative ideas and insights, enabling a quicker understanding of situations and swift decision-making. Overall, it contributes to the intangible rise of non-material combat capabilities (Fig.6).

Enhancement of physical abilities

The early development of human augmentation was initially aimed at preventive therapy for the elderly with mobility issues, enhancing productivity for individuals handling heavy loads or engaging in repetitive and prolonged tasks in industrial settings, and overcoming disabilities for those experiencing inconvenience due to lost bodily functions [23]. Representative technologies for augmenting physical abilities include strength-enhancing exoskeletons, artificial vision and hearing, rehabilitation robots, and exoskeleton devices like Lockheed Martin's HULC designed for super soldiers. Looking at the Russia-Ukraine war that started in February 2022, there are media reports stating that the number of Ukrainians who have undergone amputation surgery due to Russian attacks could be as high as 50,000, reaching a level similar to World War I [24]. While most of them have

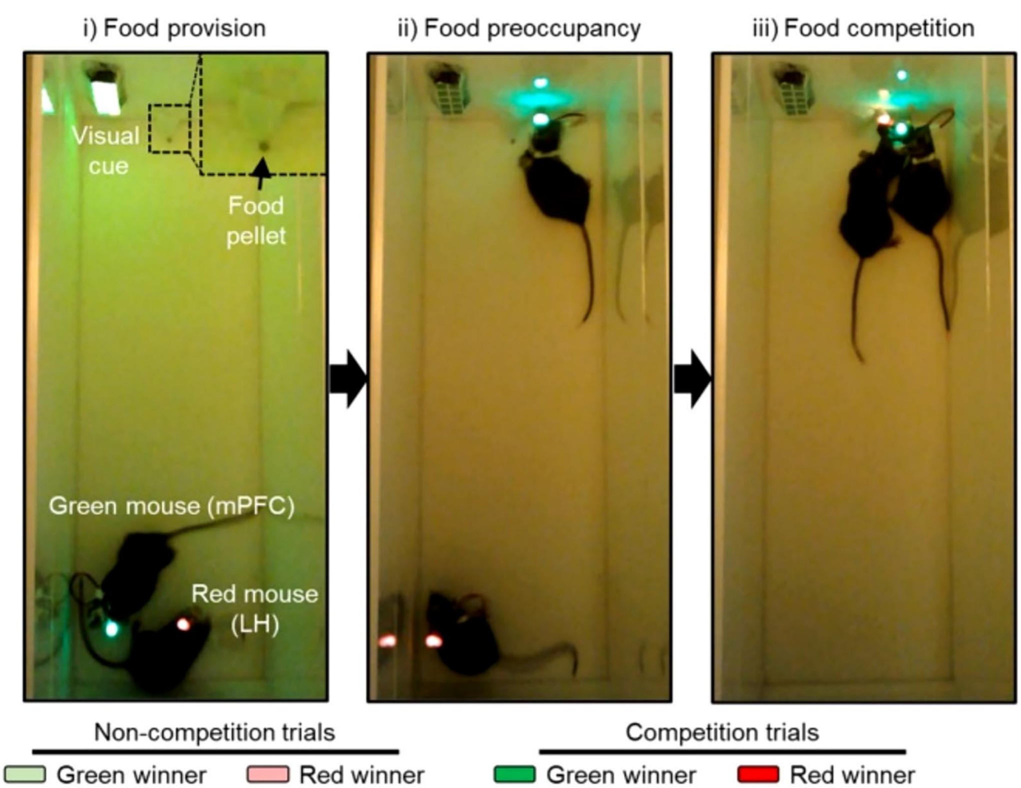

Fig. 6 Food competition between two freely behaving mice and real-time monitoring of the neural activities (reprinted from Nature Communications, Copyright (2022), with permission from Nature Communications)

been injured by shelling, missiles, and landmines, a significant number of people are struggling with depression, and trauma in their daily lives after surgery. Human augmentation technology is expected not only to assist these individuals in redesigning their lives but also to contribute significantly to alleviating depression. Recent research indicates that neurons in the mPFC (medial Prefrontal Cortex) of the brain play a positive role in perception, interaction, and competition [25]. In an experiment where two mice compete for food, injecting an appetite-suppressing drug into the LH (Lateral Hypothalamus) region of one mouse causes it to no longer participate in the food competition. When measuring signals from the mPFC area of the remaining mouse, it is observed that the firing rate of signals significantly decreases due to the absence of competition. Therefore, increasing the activity of the mPFC area, a brain region related to competition, through drug injection is possible. Based on these experimental results, it is anticipated that stimulating or delivering drugs to specific brain regions can maximize combat capabilities for soldiers engaged in combat on the battlefield. While traditional warrior platforms have enhanced combatant survivability and lethality with advanced equipment, the advancement of neural engineering is expected to elevate soldiers' morale, courage, and confidence to their maximum, contributing to enhanced combat effectiveness. Post-Traumatic Stress Disorder (PTSD) is explained and theorized to result from the interaction of various factors, including the nature of the traumatic event, personal internal factors before and after the trauma, and the interplay of these factors with environmental elements [26]. The recovery process has also been discussed as involving the interaction of multiple factors. However, a crucial aspect believed to be essential for recovery is related to the cognitive processes in the brain that continue to perceive the traumatic event as a significant threat, even when the actual threat in the present is no longer substantial [27]. Therefore, using brain stimulation or brain drug delivery technologies to address the cognitive processes involved in processing such trauma could be an effective treatment for patients suffering from PTSD. This approach may be particularly applicable to combatants experiencing severe PTSD due to combat, effectively controlling their mental health.

MEMS-based neural interface systems

MEMS-based neural interface systems are considered innovative technology for human augmentation, as they enable direct communication between the brain and computer, potentially enhancing human cognitive and physical abilities. Table 2 summarizes the Pros and Cons of MEMS-based neural interface systems. To enhance various human abilities, described above, it is crucial to record neural signals and stimulate specific brain regions accurately. Since the first silicon-based neural probe was introduced by Kensall D. Wise in 1970, recording technology has been developed [28]. Recently, Neuropixel has commercialized silicon probes with over 1,000 electrodes integrated into a single probe [29]. This probe is integrated with CMOS circuits for signal amplification beneath the electrodes. Additionally, circuits for signal amplification and processing are integrated within the probe, reducing the size of transmitted data and the number of required signal lines despite the integration of 1,000 electrodes. This achievement is made possible by leveraging advanced semiconductor technology. By utilizing the latest CMOS integration processes and MEMS-based post semiconductor process, circuits and electrodes could be integrated into small probes with a width of 70 µm.

In neural interface systems, it is very important to reduce tissue damage by the implanted probe. Specially, the silicon, hard material, may induce chronic tissue damage by continuous brain micromotion. The neural interface system developed by Neuralink is designed to minimize brain tissue damage and enable stable long-term signal measurement. Unlike traditional silicon electrodes, the electrodes used in the Neuralink system are designed in a thin thread-like form to minimize brain tissue damage upon insertion. Additionally, structures integrating electrodes with flexible materials were fabricated to minimize brain tissue damage caused by micromotions. Multiple electrodes are integrated into a single

Table 2 The advantages and disadvantages of MEMS-based neural interface systems for human augmentation

Classification	The Key elements	Content
Advantages	Miniaturization, precise maneuverability	High-precision stimulation and monitoring of specific brain regions
	High level of integration	Implementation of various sensors and actuators on a single chip, capable of performing complex neurological functions
Disadvantages	Biocompatibility issues	Inflammation, rejection response, tissue damage due to long-term use
	Technical limitations	Limitations in fully understanding and mimicking the complexity of the brain
	Ethical issues	Issues regarding the inherent value of human beings

thread, increasing electrode density, and their sizes are similar to neurons, enabling the measurement of single neural signals. These structures consist of thin film metals and polymer materials. Moreover, using rough electrode materials to increase surface area reduced electrode impedance, contributing to improving the signal-to-noise ratio (S/N), thus enhancing signal quality. Neuralink electrodes, composed of multiple thread-like electrodes, increased the number of available electrodes and electrode density.

Recent advances in neural interfaces system is currently focused on the treatment of various brain disease and overcoming of movement disorder. However, when the safety issue is resolved, these interface systems with stimulation capability will be used to enhance human augmentation and individual combat capabilities.

Conclusions and outlook

The development of advanced science and technology due to the Fourth Industrial Revolution has brought revolutionary changes not only in military capabilities but also in the application of human augmentation technology to soldiers on the battlefield. This study discusses the concept and background of human augmentation, the areas of human augmentation, and approaches to enhancing military capabilities based on neural engineering. While there are still many challenges in understanding the complex neural networks of the brain, the development of brain chips based on small and highly efficient sensors has shown the potential to detect signals from various brain areas, leading to advancements in physical and cognitive abilities. Clinical experiments using mice have demonstrated that stimulating specific parts of the brain or delivering drugs can enhance competitiveness, increase confidence and courage, and amplify fear and trauma, ultimately improving combat effectiveness. However, it is crucial that human augmentation is used only for purposes deemed necessary by the state, and efforts should be made to minimize infringements on individual privacy, as mentioned earlier. Therefore, the future challenge lies in establishing institutional measures that adhere to appropriate ethical judgments to ensure that human augmentation maintains its fundamental spirit and does not lead to the unrestricted, indiscriminate augmentation of individuals, both physically and cognitively.

Author contributions

Youngsam Yoon and Il-Joo Cho wrote the main manuscript text and prepared all figures.

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Data availability

No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate

Not applicable.

Competing interests

The authors declare no competing interests.

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