U.S. ARMY COMBAT CAPABILITIES DEVELOPMENT COMMAND
CHEMICAL BIOLOGICAL CENTER

ABERDEEN PROVING GROUND, MD 21010-5424

CCDC CBC-TR-1599

Cyborg Soldier 2050: Human/Machine Fusion and the Implications for the Future of the DOD

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October 2019

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REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
XX-10-2019

2. REPORT TYPE
Final

3. DATES COVERED *(From - To)*
Sep 2018–Aug 2019

4. TITLE AND SUBTITLE
Cyborg Soldier 2050: Human/Machine Fusion and the Implications for the Future of the DoD

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
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5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Director, CCDC CBC, ATTN: FCDD-CBR, APG, MD 21010-5424; U.S. Naval Research Laboratory; 4555 Overlook Ave. SW, Washington, DC 20375-0001; National Defense University; 260 5th Ave. SW, Washington, DC 20319-5066; U.S. Army Medical Research and Development Command; 504 Scott St., Fort Detrick, MD 21702-5000; Office of the Under Secretary of Defense for Research and Engineering; 4800 Mark Center Dr., Suite 17E08, Alexandria, VA 22350-0002; Georgetown University, 4000 Reservoir Rd., Washington, DC 20057-1409

8. PERFORMING ORGANIZATION REPORT NUMBER
CCDC CBC-TR-1599

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of the Under Secretary of Defense for Research and Engineering; 4800 Mark Center Drive, Suite 17E08, Alexandria, VA 22350-0002

10. SPONSOR/MONITOR'S ACRONYM(S)
USD(R&E)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release: distribution unlimited.

13. SUPPLEMENTARY NOTES
U.S. Army Combat Capabilities Development Command Chemical Biological Center (CCDC CBC) was previously known as U.S. Army Edgewood Chemical Biological Center (ECBC).

14. ABSTRACT-LIMIT 200 WORDS
The Office of the Under Secretary of Defense for Research and Engineering (Alexandria, VA) established the DOD Biotechnologies for Health and Human Performance Council (BHPC) study group to continually assess research and development in biotechnology. The BHPC group assesses scientific advances for improved health and performance with potential military application; identifies corresponding risks and opportunities and ethical, legal, and social implications; and provides senior leadership with recommendations for mitigating adversarial threats and maximizing opportunities for future U.S. forces. At the direction of the BHPC Executive Committee, the BHPC study group conducted a year-long assessment entitled "Cyborg Soldier 2050: Human/Machine Fusion and the Impact for the Future of the DOD". The primary objective of this effort was to forecast and evaluate the military implications of machines that are physically integrated with the human body to augment and enhance human performance over the next 30 years. This report summarizes this assessment and findings; identifies four potential military-use cases for new technologies in this area; and assesses their impact upon the DOD organizational structure, warfighter doctrine and tactics, and interoperability with U.S. allies and civil society.

15. SUBJECT TERMS
Cyborg Human/machine enhancement Biotechnologies for Health and Human Performance Council (BHPC)

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					Renu B. Rastogi
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER *(include area code)*
U	U	U	UU	42	(410) 436-7545

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

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PREFACE

The work described in this report was started in September 2018 and completed in August 2019.

The use of either trade or manufacturers' names in this report does not constitute an official endorsement of any commercial products. This report may not be cited for purposes of advertisement. Part of the work performed in this report was conducted when the U.S. Army Combat Capabilities Development Command Chemical Biological Center (CCDC CBC; Aberdeen Proving Ground, MD) was known as the Edgewood Chemical Biological Center (ECBC).

This report has been approved for public release.

Acknowledgments

The authors wish to acknowledge contributions from the following individuals: Calvin Chue (ECBC), Jason Gitlin, Brianna McNamara, Aleksandr E. Miklos (CCDC CBC), Cary Funk (Pew Research Center; Washington, DC), Rhonda Allen, Patrick Mason, Jason Aulds, Jim Carney, Shawnee Cohn, Lisa Troyer, Zarah Ahmad, Peter Carr, Joshua Swift, Malerie Stalker, Andrew Midzak, Wallace Patterson, Thomas Herzig, Dave Shepherd, Rajesh Naik, Laura Regan, Jim Cyan, Edward Perkins, Linda Chrisey, Michael Grinkemeyer, Marti Jett-Tilton, Lisa Lott, Brandon S. Martin, Mimi Strand, James Giordano, Deborah Taylor, Theresa Warfel, Anne Cheever, Fritz Schulz, Jay Bucci, Stephanie Larson, Robert McCreight, Laura R. Brosch, Haley Nolan, Nancy Kelly-Loughnane, Christian Whitchurch, Hal Greenwald, Eric Fried, Eric Erickson, Troy Alexander, Ben Lawson, and Jimmy Gollihar.

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EXECUTIVE SUMMARY

A DoD Biotechnologies for Health and Human Performance Council (BHPC; Alexandria, VA) study group surveyed a wide range of current and emerging technologies relevant to assisting and augmenting human performance in many domains. The team used this information to develop a series of vignettes as case studies for discussion and analysis including feasibility; military application; and ethical, legal, and social implication (ELSI) considerations. Ultimately, the team selected four vignettes as being technically feasible by 2050 or earlier. The following vignettes are relevant to military needs and offer capabilities beyond current military systems:

- ocular enhancements to imaging, sight, and situational awareness;
- restoration and programmed muscular control through an optogenetic bodysuit sensor web;
- auditory enhancement for communication and protection; and
- direct neural enhancement of the human brain for two-way data transfer.

Although each of these technologies will offer the potential to incrementally enhance performance beyond the normal human baseline, the BHPC study group analysis suggested that the development of direct neural enhancements of the human brain for two-way data transfer would create a revolutionary advancement in future military capabilities. This technology is predicted to facilitate read/write capability between humans and machines and between humans through brain-to-brain interactions. These interactions would allow warfighters direct communication with unmanned and autonomous systems, as well as with other humans, to optimize command and control systems and operations. The potential for direct data exchange between human neural networks and microelectronic systems could revolutionize tactical warfighter communications, speed the transfer of knowledge throughout the chain of command, and ultimately dispel the “fog” of war. Direct neural enhancement of the human brain through neuro-silica interfaces could improve target acquisition and engagement and accelerate defensive and offensive systems.

Although the control of military hardware, enhanced situational awareness, and faster data assimilation afforded by direct neural control would fundamentally alter the battlefield by the year 2050, the other three cyborg technologies are also likely to be adopted in some form by warfighters and civil society. The BHPC study group predicted that human/machine enhancement technologies will become widely available before the year 2050 and will steadily mature, largely driven by civilian demand and a robust bio-economy that is at its earliest stages of development in today’s global market. The global healthcare market will fuel human/machine enhancement technologies primarily to augment the loss of functionality from injury or disease, and defense applications will likely not drive the market in its later stages. The BHPC study group anticipated that the gradual introduction of beneficial restorative cyborg technologies will, to an extent, acclimatize the population to their use.

The BHPC study group projected that introduction of augmented human beings into the general population, DOD active duty personnel, and near-peer competitors will accelerate in the years following 2050 and will lead to imbalances, inequalities, and inequities in established legal, security, and ethical frameworks. Each of these technologies will afford some level of performance improvement to end users, which will widen the performance gap between enhanced and unenhanced individuals and teams. The BHPC study group analyzed case studies and posed a series of questions to drive its assessment of the impact to DOD programs, policies, and operations. The following are the resulting recommendations (not listed in order of priority):

1. **DOD personnel must conduct global assessments of societal awareness and perceptions of human/machine enhancement technologies.** A generalized perception exists in the United States that our adversaries are more likely to adopt technologies that U.S. populations are reluctant or unwilling to field because of ethical concerns. However, the attitudes of our adversaries toward these technologies have never been verified. Societal apprehension following the introduction of new technologies can lead to unanticipated political barriers and slow domestic adoption, irrespective of value or realistic risk. Assessment of global attitudes will predict where it may be difficult to introduce new technologies because of sociopolitical barriers to adoption and when adversarial adoption of offset technologies may likely be more readily accepted.

2. **U.S. leadership should use existing and newly developed forums (e.g., NATO) to discuss impacts to interoperability with allied partners as we approach the year 2050. This will help develop policies and practices that will maximize interoperability of forces.** The rapid development pace of cyborg technologies has implications for interoperability of military forces. The DOD requirement to maintain interoperability with allied partners within NATO and other global alliance frameworks warrants the undertaking of efforts to align cyborg assets with existing allied partnership doctrine.

3. **DOD should invest in the development of dynamic legal, security, and ethical frameworks under its control that anticipate emerging technologies.** The current legal, security, and ethical frameworks are insufficient because of the speed at which these technologies are developing in the United States and other nations around the world (allied and adversarial). Therefore, the DOD should support the development of forward-leaning policies (internal and external) that protect individual privacy, sustain security, and manage personal and organizational risk, while maximizing defined benefits to the United States and its allies and assets. Because operationalization of technology for national security is at the core of the DOD mission, these frameworks should be structured to be agile and responsive to new technologies developed within the United States or elsewhere.

4. **Efforts should be undertaken to reverse negative cultural narratives of enhancement technologies.** Across popular social and open-source media, literature, and film, the use of machines to enhance the physical condition of the human species has received a distorted and dystopian narrative in the name of entertainment. A more realistic and balanced (if not more positive) narrative, along with transparency in the government’s approach to technology adoption, will serve to better educate the public, mitigate societal apprehensions, and

remove barriers to productive adoption of these new technologies.* A more informed public will also help illuminate valid social concerns, such as those surrounding privacy, so that DOD personnel can develop mitigation strategies, whenever possible. Although not intrinsically a DOD mission, defense leadership should understand that negative public and social perceptions will need to be overcome, if these technologies are to be fielded.

5. **DOD personnel should conduct tabletop wargames and targeted threat assessments to determine the doctrine and tactics of allied and adversarial forces.** Wargames are an established mechanism to gauge the impact of asymmetric technologies on tactics, techniques, and procedures. Tabletop exercises exploring varied scenarios of the integration and use of human/machine technologies by the United States or its adversaries will predict offset advantages, identify NATO and other allied organizational interoperability friction points, and inform senior military strategists and science and technology investors. DOD personnel should support these efforts using targeted intelligence assessments of this emerging field.

6. **The U.S. Government should support efforts to establish a whole-of-nation approach to human/machine enhancement technologies versus a whole-of-government approach.** Federal and commercial investments in these areas are uncoordinated and are being outpaced by Chinese research and development efforts, which could result in a loss of U.S. dominance in human/machine enhancement technologies within the projected timeframe of this study. Near-peer dominance in the commercial sector will place U.S. interests in the defense sector at a disadvantage and could lead to an offset disadvantage in the realm of human/machine enhancement by the year 2050. A national effort to sustain U.S. dominance in cyborg technologies is in the best interests of the DOD and the nation.

7. **The DOD should support foundational research to validate human/machine fusion technologies before fielding them and to track the long-term safety and impact on individuals and groups.** The benefits afforded by human/machine fusions will be significant and will have positive quality-of-life impacts on humankind through the restoration of any functionality lost due to illness or injury. The military community will also see capability opportunities that will impact operations and training. As these technologies evolve, it is vital that the scientific and engineering communities move cautiously to maximize their potential and focus on the safety of our society. Commensurate investments in these areas will work to mitigate the misuse or unintended consequences of these technologies.

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*Wurzman R.; Yaden D.; Giordano J. Neuroscience Fiction as Eidolá: Social Reflection and Neuroethical Obligations in Depictions of Neuroscience in Film. *Camb Q Health Care Ethics–Neuroethics Now* **2017,** *26* (2), 292–312.

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CONTENTS

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CYBORG SOLDIER 2050: HUMAN/MACHINE FUSION AND THE IMPLICATIONS FOR THE FUTURE OF THE DOD

1. INTRODUCTION

The Office of the Under Secretary of Defense for Research and Engineering established the DOD Biotechnologies for Health and Human Performance Council (BHPC) study group to continually assess research and development (R&D) in biotechnology. The inter-agency group was asked to study the fields of life sciences that are applicable to health and human performance to identify potential risks and opportunities. In addition, the group was required to provide recommendations to senior leadership on how to mitigate adversarial threats and maximize opportunities for future U.S. warfighters.

At the direction of the BHPC Executive Committee, the BHPC study group conducted a year-long research study entitled “Cyborg Soldier 2050: Human/Machine Fusion and the Impact for the Future of the DOD” that is documented in this report. The primary objective of this effort was to determine the potential of machines that are physically integrated within the human body to augment and enhance the performance of human beings over the next 30 years. The group was tasked to forecast technology advances and corresponding potential military applications for the year 2050 and to identify related ethical, legal, and societal implication (ELSI) considerations. In this report, we summarize the BHPC activities and findings; identify four potential future military-use cases for new technologies in this area; and assess their impact upon the DOD organizational structure, warfighter doctrine and tactics, and interoperability with allies and civil society.

2. SCOPE AND PURPOSE OF THE STUDY

In discussions on human/machine enhancement, we often hear the term cyborg. The word was first used in a 1960 NASA study on long-term space travel authored by Manfred Clynes and Nathan Cline.[1] The word is a portmanteau formed from “**cyb**ernetic **org**anism” and can be simply defined as an organism that is optimized by dynamic interactions of its organic (flesh) and biomechatronic (machine) parts. It has been said that present-day technology has already created populations of humans that are technically cyborgs. Biologist and philosopher Donna Haraway discusses this in her work, “A Cyborg Manifesto”, by recognizing that someone with a cardiac pacemaker or implantable cardioverter-defibrillator would be considered a cyborg. These devices measure voltage potentials in the body, perform signal processing, and can deliver electrical stimuli using synthetic feedback mechanisms to keep a person alive.[2]

Although interesting, these arguments have been set aside in this study because our use of the term cyborg is intended to envision a grander and fundamentally more complex future involving human/machine technologies over the next 30 years. The cyborg technologies assessed in this study go beyond augmentation, which restores function from injury or disease, and are envisioned to enhance performance through a range of modifications from the functional to the radically structural beyond the normal baseline for humans.[3] One can also assume that aspects of cyborg capabilities will be enabled through the use of genetic engineering, synthetic biology, nanotechnology, artificial intelligence, or any number of emerging technologies. Discussions of these domains were set aside, except those related to 2050 technology predictions, which assumed sound science and reflected accurate assessments of ongoing global R&D efforts. This study does not focus on the path scientists and engineers will take to achieve human/machine enhancement; rather it highlights the impact of this development on the DOD and U.S. society. The primary objectives of this study are to predict the direction cyborg technology will take within the next 30 years, determine how that could fundamentally impact national security, and make recommendations to senior DOD leadership on how to safeguard the United States and mitigate the threat posed by near-peer exploitation of these technologies. As a critical part of the assessment, the BHPC also identified ELSI considerations related to the fielding of these technologies within the DOD.

3. STUDY DESIGN

The BHPC study group developed analysis reports based on predictions of technologies capable of enhancing human performance in the present day or potentially within the next 30 years. Each aspect includes technology prediction and concrete examples by which to highlight and address ELSI concerns.

The BHPC study group used a capabilities-based approach to design these predictive case studies. The following individual capabilities were prioritized from "most impactful" to "least impactful" on the battlefield, should a warfighter be enhanced above baseline performance:

1. situational awareness,
2. strength and speed,
3. imaging and sight,
4. communication,
5. physiology (endurance/sleep/health),
6. virtual (avatar) control,
7. attention and memory,
8. learning, and
9. olfaction (sense of smell).

These prioritized capabilities prompted the development of four vignettes based upon emerging trends in global human/machine enhancement research. The following four case studies, together with their military applications, are described in detail in Section 6:

- ocular enhancements to imaging, sight, and situational awareness;
- restoration and programmed muscular control through an optogenetic bodysuit;
- auditory enhancement for communication and protection; and
- direct neural enhancement of the human brain for two-way data transfer.

4. DIRECT NEURAL ENHANCEMENT OF THE HUMAN BRAIN FOR REMOTE TWO-WAY DATA TRANSFER

These case studies indicated the following:

- they predicted where technology is likely to yield an outcome by the year 2050 and the capabilities and limitations that would result from the fielding of these technologies;
- they focused on the technological advances in military capabilities that would fundamentally alter the balance of power or change the nature of warfare in a revolutionary manner in comparison with traditional military hardware; and
- they provided concrete examples by which to test ELSI frameworks and identify security and ELSI considerations.

With the technology predictions in hand, the BHPC study group convened panels of multidisciplinary experts from various federal inter-agencies and selected specialists from academia and industry. For several months, the group assessed current literature and research and documented issues likely to arise from the introduction of cyborg technologies into society. Ultimately, these assessments were grouped into five areas: perceptions and politics, legal and privacy issues, safety and security, military and civilian integration, and ethical considerations.

Finally, the BHPC study group convened a workshop in which key participants presented the results of their initial research to 50 subject-matter experts for further discussion and analysis. Technology predictions and recommendations were presented, and anonymous group feedback was collected to gather additional perspectives from the team. During the workshop, the study group posted statements on the future of cyborg technology, which allowed participants to vote or make additional observations for the purpose of shaping the final suggestions within the study. The nature of this study and the workshop that followed were such that the observations and recommendations contained within this report reflect contributions from a diverse group of experts and are not solely derived from members of the BHPC study group.

5. TECHNOLOGY PREDICTIONS FOR 2050

The case studies are discussed in detail in this section. The tactical applications of the technology used and the advantages it would confer to an individual and the military unit it exists within are described.

5.1 Case Study No. 1: Ocular Enhancement for Imaging, Sight, and Situational Awareness

Tactical employment: In this scenario, individual vision is enhanced to enable sensory perception beyond the normal visible spectrum. Enhanced individuals would also have the ability to analyze images from various wavelengths to discriminate targets and allow identification in complex and cluttered environments. Computational capabilities, which would allow for target identification, selection, and data sharing with other individuals or military systems, are envisioned.

Future battlefields in 2050 are projected to be dense, urban environments or subterranean megacities that will challenge identification and tracking of targets. This ocular enhancement will offer small, dismounted teams the ability to acquire and share data in real time. Fast-moving expeditionary units will likely employ enhanced individuals as part of teams that are engaged in a multi-domain battle space in which communications are anticipated to be contested or denied. The enhanced individual would be programmed to be part of the expeditionary unit and would be capable of performing functions autonomous of external data feeds. Therefore, the enhanced individual would provide intelligence data drawn from multiple sensory fusion inputs. In short, the individual possessing the ocular enhancement would provide the squadron with a portable sensory-fusion capability.

Ocular enhancement would be an attractive medical option in situations where the eye tissue has been damaged or destroyed by injury or disease. It is deemed unlikely that individuals would willingly undergo removal of healthy tissue in an area considered to be sensitive. However, the central and critical role that vision plays in society would likely motivate warfighters who have lost part or all of their vision to voluntarily undergo surgery that would restore or even improve their ability to see.

Technical Description: The enhancement technology is likely to manifest itself in one of two ways. In the first manifestation, an ocular enhancement system would overlay the ocular tissue and retain use of the retinal walls within the existing structure, similar to systems used in ongoing research to treat adults with advanced retinitis pigmentosa.[4] Data streams would be overlaid against the retinal wall and transduced through the optic nerve, where input is interpreted by the brain. It is unlikely that these data inputs would be perceived in the same way that visual light is understood by the brain. In this respect, the warfighter would have to learn how to understand and interpret what the brain is being fed as a raw data stream. Under this situation, the retinal tissue could be altered such that other wavelengths could be interpreted to include infrared regions and beyond. Such capabilities are likely to be available, and they could mature by the year 2030 given that research efforts are already under way at the present time.

In the second, more complex manifestation, which is anticipated to be mature by the year 2050, the retinal wall is not retained. In this situation, the eyeball itself is completely replaced, and data feeds pass directly into the optical nerve bundle behind the eye. The sensory input for visualization would be completely mechanical or electronic in composition, which would allow data feeds of all types and across all spectra including those previously not capable of being visualized by humans. The fundamental challenge that will be overcome by 2050 is the ability to feed data directly from an inorganic sensory system into individual neurons within the optical nerve bundle. The development of high-bandwidth implantable interfaces that stimulate nerves at the single neuron level will facilitate two-way data transfer that is not currently possible. In essence, the eye would be completely artificial and capable of pulling in any manner of sensory data and feeding it directly into the brain for interpretation.

5.2 Case Study No. 2: Restoration and Programmed Muscular Control through an Optogenetic Bodysuit Sensor Web

Technical Description: In this scenario, muscle control is enhanced through a network of emplaced subcutaneous sensors that deliver optogenetic stimulation through programmed light pulses. This enhancement is best described as an implanted digital sensing and stimulation system that is coupled with external sensors (e.g., boot inserts and wearables), which are linked to a central computational controller. In effect, the human body would have an array of small optical sensors implanted beneath the skin in the body areas that need to be controlled. These sensors could be manifested as thin optical threads that are placed at regular intervals over critical muscle and nerve bundles and are linked to a central control area designed to stimulate each node only when the muscles below it are needed. Optical control would occur across the network of optical threads in a programmed manner to effect a fluid muscular action in a choreographed "dance." Such a network of implantable muscle sensing, computation, and stimulation provides a closed-loop suite that could be used to decrease injury and mortality rates for soldiers through automated hazard avoidance. The network would also enhance their physical capabilities on the battlefield.

Tactical employment: An optogenetic control network could be used in several ways. The most likely would be in the restoration of lost function due to injury of muscles or nerves. Musculoskeletal injuries are the second leading cause of lost duty time in the U.S. Armed Forces.[5] An optogenetic augmentation of the affected area would restore function while healing and treatment simultaneously continue. It could even provide a long-term replacement treatment for a permanently damaged capacity.

As the technology develops toward the year 2050, optogenetic body control could help respond to the persistent demand for warfighters to perform increasingly challenging tasks that often push them to the limits of their physical capability. Ongoing efforts to develop warfighter exosystems to reduce energy expenditure have revealed that current technologies often impede operator performance and increase metabolic costs.[6] An optogenetically controlled body suit could be used to sense an individual's condition and provide a real-time interface between the human and the exosystem. This human enhancement would allow dynamic adaptive coupling of the human body with an external exosystem, lead to physical behaviors that are more stable and agile, and optimize energy expenditure in operational environments.

Optogenetic musculoskeletal control systems would not only allow warfighters to interface with external systems that are not permanently adhered to their bodies, but could also be programmed to control their bodies to perform complex tasks for which they are not accustomed. The optogenetic controller would, in effect, take control of the motions of a warfighter's limbs, thereby allowing a novice (i.e., the warfighter) to perform functions professionally.

5.3 Case Study No. 3: Auditory Enhancement for Communication and Protection

Tactical employment: In this scenario, enhancement of auditory capabilities would occur through direct replacement or modification of the middle-ear bones and the cochlea.

The enhancement would afford individuals greater dynamic range of hearing, which would protect or filter overexposure and increase sensitivity to low-amplitude sounds. As the technology matures, it could expand the range for sensory perception to what are currently infrasonic and ultrasonic levels. In addition to these enhancements, significant potential exists for advances in communication through external processors and imagined or covert speech, as a component of neural signaling.

Battlefield-associated hearing loss due to acute or prolonged exposure to high-intensity sounds, such as gunfire, explosions, or military machines, is one of the most prevalent service-connected disabilities for U.S. veterans. A 2012 study suggests that ~10% of veterans suffer from tinnitus, whereas ~6% of veterans are diagnosed with some level of hearing loss.[7] Existing technology, such as the Army-sponsored Tactical Communications and Protective System, affords some protection; however, the existing technology does not offer enhanced capabilities to the user. Direct modification of an individual's inner or mid-ear regions will allow for implant-controlled protection from high-intensity noises. It could also significantly improve situational awareness through the ability to identify and amplify low-intensity sounds, positioning and localization from passive sensor transmissions or echolocation, and advanced communication capabilities.

The current level of invasiveness suggests that this technology would only be employed by individuals with significant hearing loss. Direct replacement or modification of both inner and mid-ear components would be irreversible; therefore, those with acceptable current auditory capabilities would be unlikely to receive this type of enhancement. This assessment, however, is for existing or near-future technology. Advances in external processor capabilities and minimally invasive electrode implantation in neural networks will likely make these technologies more accessible to the general population by the year 2050.

Technical description: Cochlear replacement to treat injury-associated or otherwise acquired moderate-to-severe hearing loss is currently an accepted method of restoring hearing function. An external sound receiver worn behind the ear (typically) converts sound to a digital signal, which travels to an implant within the inner ear that is used to transmit electrical signals directly to the hearing nerves. Despite the success in restoring some function, current recipients can still experience difficulties in multi-talker scenarios or in situations with high background noise, although research suggests that it is possible to track auditory attention (i.e., the direction or specific source to which an individual is listening).

For military personnel, auditory enhancements would afford protection from high-intensity noises, provide a wider dynamic range of detectable sounds, and afford integrated-communication capabilities. In the near-term (present day to 2030), it is anticipated that the enhancement will be coupled with networking capabilities and will be used to track human detection of salient objects in an acoustic environment. In squads with limited enhanced personnel, enhanced individuals could detect salient auditory information in the environment and relay it to other squad members using conventional forms of communication. In squads with multiple enhanced individuals, acquisition and distribution of auditory cues to spatially separated individuals could direct attention across an entire squad to actionable stimuli.

Later iterations of auditory enhancements would likely target two key areas: (1) the capability for communication through imagined or covert speech and (2) implants that are significantly less invasive or reversible. With regard to imagined speech, the BHPC study group predicted that within this extended timeline (to 2050), significant advances in the understanding of neural pathways will enable not merely improvements to an individual's auditory signal transduction but also conversion and transmission of these signals to others across distances.[8] This capability could lead to increased acceptance and adoption of this enhancement in areas outside the military, such as intelligence officers, police forces, and others who would benefit from using imperceptible forms of communication. Technologies that allow real-time translation of multiple languages would be useful to military operators as well as civilians. The BHPC group sees potential within the 2050 timeline for advances in the external processor unit and its method of interfacing with auditory nerves and other neural transmission pathways. This way, this technology could be less invasive than cochlear replacement and more likely to be reversible. Electrodes that directly interface with neural pathways could be implanted with a minor surgical procedure and potentially, could be removed with minimal adverse effects.

5.4 Case Study No. 4: Direct Neural Enhancement of the Human Brain

Tactical employment: In this scenario, neural implants for brain–computer interfacing (BCI) would allow for seamless interaction between individuals and secondary assets (machines). This control could be exerted upon drones, weapon systems, and other remote systems operated by an enhanced individual. The enhancement would not simply entail user control of equipment (brain to machine) but also transmission to operator (machine to brain) and human to human (command and control dynamics) to enhance situational awareness as drone, computational analytical, and human information is relayed to the operator.

Use of remote weapon systems and unmanned vehicles is increasing on the modern battlefield. Vehicle- and infrastructure-associated remote weapon systems allow for operators to effectively control the battlefield from a distance in relative safety. Similarly, unmanned vehicles will play an invaluable role in reconnaissance and long-range targeting of enemy infrastructure, equipment, and personnel. Our current state of technology allows remote weapon systems and unmanned vehicles to be controlled by fixed or portable workstations. Although these current systems are effective, they are hindered by the complexity of user interfaces and the limited information that can be conveyed to the user. Neural enhancement through implantation of modulatory electrodes in the brain will allow for rapid interaction between machine and operator through a read/write type of mechanism.[9] These will enable more rapid and integrated control of multiple assets by the enhanced operator, thus improving battlefield awareness and warfighter lethality.

Brain activity will be monitored noninvasively through electrodes placed upon the scalp or skull or more invasively through the direct implantation of electrodes to the brain surface or deeper structures and networks. At present, researchers have not been able to determine whether the implantation of electrodes is reversible or to what extent affected neural networks adapt to the presence of an implant, thereby complicating removal. As this technology matures, it is anticipated that specialized operators will be using neural implants for enhanced operation of assets by the year 2030. These operators will include teams from the Special Forces, military pilots, operators of unmanned aerial vehicles (UAVs) or unmanned surface vehicles (USVs) such as drones, and intelligence personnel.[10] The BHPC group predicts that by the year 2050, significant advances will be made in the understanding of the neural network and neural implant technology. With greater understanding, it is anticipated there will be larger deployment of these technologies to military forces, enabling use-controlled operation of weapon systems, network communication and interaction (e.g., corpsmen speaking with doctors or specialists in hospitals to aid in field treatment of combat injuries), and improved warfighter awareness through machine to brain (and machine-enabled remote brain to brain) communication via the use of distributed sensors, transmitters, and reconnaissance drones.

Technical description: Neural implants to enable BCIs provide the brain with input and output channels that are dependent on brain activity rather than peripheral nerves and muscles, which eliminates the need for conventional delivery mechanisms such as joysticks or keyboards.[11,12] Neural implants to facilitate BCI can be broken into five components: signal acquisition, signal preprocessing, feature extraction, classification, and signal transmission.[13] The signal acquisition component can be invasive and involve methods that use microelectrodes directly implanted into regions of the brain or extended across the surface of the brain. Noninvasive methods in which electrodes are positioned on the scalp can also be used. The level of invasiveness directly correlates with the quality of the signal received and transmitted to the processor and classifier components.

For the warfighter, neural implants would have broad battlefield applicability. External processors and transmitters would allow for interaction with battlefield assets (i.e., weapon systems, reconnaissance drones, UAVs, and unmanned marine vehicles [UMVs]) as well as personnel within proximity or across distances through hierarchical relays with a central network. Early deployment of BCIs in enhanced individuals would be limited to small-scale specialized teams in which one or more enhanced personnel would offer squad support through asset control. The level of invasiveness of early iterations and the potential irreversibility of these implants may limit acceptance by military personnel and society, although specialized teams (Navy SEALs, Army Rangers, etc.) may be more inclined to accept these technologies if they could provide significant improvements in capability, lethality, survivability, and overall battlefield superiority.

Improvements in neural implant technology could be significant by the year 2050. Anticipated improvements would focus on reducing the level of invasiveness of the implant itself. This could be accomplished through location-specific assembly of electrodes using biocompatible nanoparticles that can be directed through an external force (doped iron oxide nanoparticles that can be positioned through the use of directed magnetic fields) or through improvements to the signal acquisition capabilities of externally placed electrodes and processors. The study group expects that warfighter needs will influence these technological advancements; however, such advances would plausibly lead to revolutionary changes in how society interacts with machines on a daily level. These technologies (personal robots, entertainment options, and vehicles) would be driven and sustained by commercial entities.

6. DISCUSSION

6.1 Societal Perceptions as Impediments or Drivers of Cyborg Soldiers

During the early stages of this study, there was much discussion about near-peer competitors and adversaries. In addition, questions were repeatedly asked about potential willingness to undertake forward-leaning research in genetic engineering and invasive human/machine enhancements that the U.S. research community would be more hesitant to conduct because of differing ethical frameworks, regulatory requirements, and social attitudes. Within weeks of initiating this study, a Chinese research team led by He Jiankui announced the germline manipulation of human embryos for the stated purpose of avoiding human immunodeficiency virus infection transmitted by a mother to a baby.[14] Months later, a Russian scientist, Denis Rebrikov, claimed it was his intention to implant gene-edited embryos into the wombs of women.[15] In 2017, the BHPC study group discussed genetic manipulation of a dog's myostatin genes to increase canine body musculature severalfold, resulting in what many considered to be a perversion of nature that evoked concerns about super soldiers.[16]

Among the BHPC study group, these perceptions about near-peer adversaries' strategic intent were widely but not universally accepted; however, ultimately, they were based on anecdotes (i.e., examples of individual scientists pursuing their own research). Prior and ongoing work by study group members has demonstrated (1) total involvement of China's governmental/political institution(s) in all aspects of domestically conducted science and technology research, development, and production[17] and (2) explicit statements of differing cultural values, norms, and needs that underlie distinct ethicolegal principles governing the conduct of research.[18–20] However, the following questions were asked: Had anyone ever systematically assessed global perceptions on what was ethical and what was not? To what extent, if any, are the R&D activities of different regions of the world constrained by different moral codes or swayed by popular regional opinion? What characteristics, such as education, religious beliefs, or doctrine, affect willingness to allow the use of advanced technology to enhance the human condition? and To what extent do the attitudes among members of the public impact the activities of a particular government?

To shed light on this topic, Cary Funk, the Director of Science and Society Research at the Pew Research Center (Washington, DC), was invited to join the study group. Dr. Funk specializes in measuring views on public trust in science and had concluded a 2016 survey of 4726 people within the United States that focused on understanding attitudes about human enhancement technologies. The survey examined public attitudes about the potential use of three emerging technologies that could fundamentally improve human health, cognitive abilities, and physical capacities. The technologies were (1) implanting brain chips to give people a much improved ability to concentrate and process information; (2) transfusing synthetic blood to give people much greater speed, strength, and stamina; and (3) editing genes to give babies a life with much reduced risk of serious disease.

The study, "U.S. Public Wary of Biomedical Technologies to 'Enhance' Human Abilities," showed that the majority of Americans greeted the possibility of these breakthroughs with wariness and worry rather than enthusiasm and hope.[21] A majority of U.S. adults said that they would be “very” or “somewhat” worried about brain chips (69%) and synthetic blood (63%), whereas no more than half said that they would be enthusiastic about each of these developments. Some people said they would be both enthusiastic and worried, but overall, concern outpaced excitement. Public opinion was closely divided when it came to the fundamental question of whether these potential developments are “meddling with nature” and crossing a line that should not be crossed, or whether they are “no different” from other methods that humans have tried to better themselves over time. People’s views differed depending on how religious they are. The more religious Americans were, on average, the less affirming they were of these enhancements. People with deep religious commitment were less likely than those with less religious commitment to want any one of the three potential enhancements. By contrast, majorities of those with less religious commitment were more inclined to see the potential use of these techniques as just the continuation of a centuries-old quest by humans to try to better themselves.[22]

These results suggest that a person’s willingness to accept or reject the use of a technology for the purpose of human enhancement is based on awareness and understanding of the technology and the degree of religious commitment. In the group’s discussions, other factors did not present significantly high correlations, and it is important to note that Dr. Funk’s survey was conducted within the United States. Neither Dr. Funk nor any other member of the study group was able to identify a study that collected similar data from residents of other countries that were scientifically rigorous enough to be of value. The group further noted that future surveys on near-peer adversary populations would be controlled. Moreover, the attitudes and opinions of the general public do not necessarily represent what government authorities or research teams are willing to pursue. U.S. leadership has very little data about what residents of other countries are willing to accept with regard to the use of human/machine enhancement technologies or to what extent their political and military leaders and scientific community are willing to support this technology. With this in mind, the group made the following recommendation:

> The DOD should initiate a global survey of societal awareness and perceptions of human/machine enhancement technologies. Assessment of global attitudes will predict where adoption may be difficult to introduce and when adversarial adoption of offset technologies is likely to be more readily accepted.

6.2 Interoperability and the Politics of Enhanced Soldiers

The pace of development in cyborg technologies is expected to accelerate over the next 10–15 years, driven by commercial medical applications. Adoption of these maturing technologies by global defense forces with commensurate protection of proprietary and classified technologies is deemed likely. Adoption of new and potentially sensitive technologies can have implications for interoperability of military forces. The DOD requirement to maintain interoperability with allied partners within NATO and other allied partnership frameworks would suggest that efforts to align cyborg assets with existing or newly developed doctrine should be undertaken.

The study group recommended that U.S. leadership use current allied forums (e.g., NATO) to discuss impacts to interoperability with allied partners as we approach the year 2050. This will help in the development of policies and practices that will maximize interoperability of forces.

Interoperability of military units in a tactical sense is not the only hurdle that must be overcome when bringing together populations from different countries. The policies of countries are dependent upon the shared social norms and beliefs of the population, and these are not guaranteed to align on the issue of human/machine enhancement technologies.[23] Given that the measured attitudes from the Pew Research Center's study on cyborg technologies indicated clear alignment to religious commitment, allies with a strong history of religiosity may be more reluctant to accept foreign cyborg soldiers operating on a shared military base within their borders. Judging from current postures and practices of key strategic competitors,[24–26] the study group postulated that it is unlikely that the global community will establish consistent and harmonized approaches to integrating human/machine enhanced warfighters. This lack of agreement will present challenges to the deployment of these assets in the years leading up to 2050. A robust multinational dialogue that identifies acceptable legal, moral, philosophical, and ethical frameworks for the use of these technologies in national defense may prepare the global community for these eventualities.

Aside from allied acceptance and military interoperability is the global political costs of fielding cyborg military assets. The workshop participants unanimously anticipated that state and non-state adversaries will seek to use U.S. deployment of enhanced warfighters to undermine U.S. interests and stigmatize the DOD as unethical. Given the results of the Pew study, religion seems a likely platform to galvanize these arguments against U.S. interests with entertainment and social media reinforcement. Mass media, including film and literature, is also a known stage for demonization of cyborgs. From Frankenstein to the Terminator, the message is often that technology's integration with the human body robs the human spirit of its compassion and leads to violence and grave, unintended consequences. However, fiction can also reflect imaginative applications of emerging technologies as well as real concerns with those technologies. For these reasons, fiction can be a powerful tool for engaging the public in discussions of bioethics.[28–30] A better-informed public that creates and consumes media related to emerging technologies may thus help DOD and its partners forecast ELSI concerns to mitigate problems early in the development of enhancement-related capabilities.

The study group recommended that efforts should be undertaken to reverse the negative cultural narratives of enhancement technologies and leverage media as a means of engaging the public. Across popular social and open-source media, literature, and film, the use of machines to enhance the physical condition of the human species has received a distorted and dystopian narrative in the name of entertainment. More accurate depiction of technology and its applications in fiction and nonfiction media could lay the groundwork for a new generation that sees opportunity for societal benefits in cyborg technologies. If technology is to become a more intimate partner in the physical enhancement of the human species, then DOD personnel must help alter distorted cultural narratives. A realistic, balanced (if not more positive) narrative will serve to better educate the public, mitigate societal apprehensions, and remove barriers to productive adoption of these new technologies.[31] Although not intrinsically a DOD mission, defense leadership should understand that if they intend to field these technologies, public and social perceptions will need to be understood and overcome.

6.3 Legal and Privacy Implications for Cyborg Technologies

Many legal scholars will attest that the legal frameworks governing the use of technology (such as cell phones, email, and social media) are inadequate. As the pace of technological development accelerates and human/machine enhancements become a reality in the years leading up to 2050, it is almost certain that legal frameworks will continue to be outpaced and face new challenges. In their 2014 study, "Our Cyborg Future: Law and Policy Implications", Benjamin Wittes and Jane Chong discuss how the prolific use of cell phones and wearable devices bring technology closer to the human race than before and suggest that we are, in effect, approaching a state in which we are already "juvenile cyborgs".[27] They suggest that the introduction of more advanced human/machine enhancements, such as those proposed in this study, will create unique legal challenges because of data generation, which lies at the heart of machines.

> The first consideration that must factor into our discussion is that cyborgs inherently generate data. Human activity by default does not, at least, not beyond footprints, fingerprints, and DNA traces. We can think and move without leaving meaningful traces; we can speak without recording. Digital activity, by contrast, creates transactional records. A cyborg's activity is presumptively recorded and that data may be stored or transmitted. To record or transmit data is also to enable the collection or interception of those data. Unless one specifically engineers a cyborg to resist such collection or interception, it will by default facilitate surveillance. In the event a cyborg is engineered to resist surveillance, data are still created. In other words, a world of cyborgs is a world awash in data: data about individuals, data of enormous sensitivity, and the further cyborgidization progresses, data of ever-increasing granularity.
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> Thus, the most immediate impact of cyborgidization on the law of surveillance will likely put additional pressure on the so-called third-party doctrine, which underlies a great deal of governmental collection on transactional data and business records. Under third-party doctrine, an individual does not have a reasonable expectation of privacy with respect to voluntary disclosure of information to a third party (e.g., a bank or a telecommunications carrier), and the Fourth Amendment, therefore, does not regulate the acquisition of such transactional data from those third parties by governmental investigators.[27]

The authors go on to argue that the more essential the role machines play in our lives, the more integral the data they produce are to our human existence. In addition, the devices become more inextricably intertwined with us: socially, physically, and biologically. They suggest that it is less plausible that we would voluntarily turn over the data produced by these devices to a third party or permit someone else to do so. If this is true, what are the implications for the enhanced individual? Furthermore, what are the implications of data generated by a member of the armed forces? For example, who owns such data, and for what purposes can these data be used? From a legal perspective, enhanced humans will likely generate huge amounts of data, which makes them uniquely susceptible to targeting and surveillance. Current legal frameworks are not structured to handle such scenarios.

Conversely, consider the privacy aspect of the legal argument in which cyborg technology inherently collects data from those around the enhanced individual. Some of the technology predictions within this study envision human/machine enhancements in which audio, video, geolocation, and time stamps could be recorded and distributed. From a national security perspective, this enhances situational awareness and clearly has military applications. But in a civilian setting, such as in a coffee shop or the gym, it will have other implications, including impact on bystanders. Although an individual volunteers for enhancement and agrees to any corresponding collection of his or her personal data, bystanders are unlikely to have granted the same permission. Deliberations at the Cyborg Soldier 2050 Workshop raised other scenarios that are likely to arise:

- If an enhanced warfighter is caught and captured, does he have the same protections under the Geneva Convention, and will his enhanced status alter the treatment he is likely to receive?
- Can a person be prevented from having or using an enhancement under special circumstances (such as entering a bank or sensitive compartmented information facility, gambling in a casino, taking a test, or negotiating a contract)?
- Can an employer discriminate against an enhanced or non-enhanced person? Can a business refuse to serve an enhanced person? Can the enhanced person be paid more for services than a non-enhanced person working in the same capacity?
- Are an enhanced individual's capability to monitor, record, and communicate conversations and images bound by the same legal frameworks that govern wiretapping and privacy laws for cell phones and other recording devices?
- Is the misuse of enhanced technology on the part of an employee grounds for deactivation or removal of the technology?
- Is there a legal precedent for passing laws that restrict or modulate technology integral to our bodies?
- Who is liable for any accidents caused by malfunctioning of the technology?
- Can a person sign away legal authority or control over something inside his body (i.e., akin to a delegation of authority or responsibility)?
- Will people be required to disclose the presence of enhancements within their bodies? If so, when, why, and to whom?

- Can someone be screened to reveal an enhancement that is NOT visible through the use of a metal detector or body scanner? What is the expectation of privacy for enhanced individuals and the people interacting with them?

Clearly, current legal frameworks are insufficient to predict the myriad challenges to privacy and security that will arise from these situations.[28–30] As a result, the BHPC study group made the following recommendation: The DOD should invest in the development of dynamic legal, security and ethical frameworks that anticipate these new technologies under its control.

The current legal, security, and ethical frameworks are insufficient given the speed at which these technologies are developing in the United States and other nations (allied or adversarial). Therefore, the DOD should support the development of forward-leaning policies (internal and external to the department) that protect individual privacy, sustain security, and manage personal and organizational risk. Because operationalization of technology for national security is at the core of the DOD mission, these frameworks should be structured to be agile and responsive to new technologies that are developed within the United States or elsewhere. Moreover, frameworks should be adaptable to the entire life cycle of technological advancement from early-stage research through fielding and operational use.

7.4 Safety and National Security

The overall strategic significance and game-changing aspects of enhanced soldiers and technologies aimed at developing cyborg soldiers may be viewed as a threat by some. The threat perspective is supported by the argument that cyborg technology is almost impossible to detect, very difficult to deter, and therefore, highly challenging to defend against. If the strategic landscape after the year 2025 changes sooner than expected or contains ambiguous threats against which we lack capabilities to detect and defend, the balance of power as well as the very definition of "asymmetric warfare" will be forever altered. What is clear is that the introduction of human/machine enhancements into military and civilian populations will create new vulnerabilities that will need to be mitigated by security architectures. Cyborg technologies will create a world awash in data in which individuals will record images and audios or generate geographic coordinates and time stamps. In some cases, these processes will occur automatically in the background without willful intention as part of the course of daily events (called "transactional records" by Wittes and Chong).[27] To record or to transmit data is also to enable collection or interception of that data. Unless one specifically engineers the cyborg to resist such collection or interception, it will by default facilitate surveillance. Relatedly, due to their surveillance capabilities, cyborgs could be selectively tracked and targeted unless appropriately shielded.

From a national security perspective, adversaries may piggyback surveillance and tracking technologies within implanted cyborg mechanisms. In the words of one study participant, "If I can't walk into a sensitive compartmented information facility wearing an iWatch or carrying a cellphone, how will security be confident it is safe to allow a cyborg to walk in there?" In short, an enhanced soldier with a machine interface presents a potential security risk and complicates work within secure environments.

Machines respond to commands, and if command and control are hacked, the human/machine will be compromised. Hackability by external forces could generate the fear of control by others. Even if this risk can be mitigated through enhanced encryption methods, variable authentication requirements, or other methods, the perception that control could be subverted may lead to issues of trust among peers. For example, if a hostile actor could override an optogenetic body suit or neural implant that controls muscle movement, this could not only create a true threat to the individual, organization, and mission, but could promulgate fears among the ranks of non-enhanced and enhanced individuals.

Lastly, consider that these are advanced technologies that can and will travel the world outside of traditional security controls put in place to prevent exploitation. Technology ownership and chain of command of an enhanced soldier is nontraditional (e.g., an enhanced soldier plans a vacation to foreign countries, which poses diplomatic and security risks). Thus, there is a need for increased and sustained trust at the individual-user level that the system will perform reliably (i.e., that verification and validation have been done) in and across a range of settings and circumstances.

6.5 Military Opportunities to Enhance Capability

Human augmentations and enhancements carry a number of security and privacy concerns at the national and global societal level. These technologies, however, also offer significant advantages to the DOD and other national agencies. In addition to general enhancements of warfighter performance, many enhancements have the potential to offer new opportunities to significantly improve warfighter survivability, allowing them to operate safely and securely in austere environments.[10,31] One could argue that failure to invest in responsible development of these potentially lifesaving technologies would be unethical.

With highly variable combat environments, conditions, and adversaries, military technology is rapidly advancing to provide enhanced situational awareness to warfighters. DOD forces regularly deploy a wide array of UAVs and UMVs to collect and relay data for assessment. At present, the intelligence gathered by UAV assets is often collected at a central location and then disseminated to forward operators through conventional communication networks, which can prove limiting in some situations. As discussed in case study no. 4, neural enhancements, portable independent communication systems between squads and squad members, as well as with computer systems (such as UAVs) could enable warfighters to operate "off the cloud" or "on the edge." In a multi-domain battle space in which communications and movement could be contested by fast-moving expeditionary forces, these types of portable communications could lead to enhanced targeting, tracking, and situational awareness organic to the squad level, thereby enabling rapid decision-making and operational flexibility.

The ability to passively record environmental situations and personal interactions and observations without external equipment or devices would also be invaluable to clandestine surveillance. In dense urban environments, operators would be able to seamlessly move through crowded city streets capturing environmental intelligence, targeting conversations, and acquiring other valuable information that would be digitally stored for later analysis and interpretation. In addition, although clandestine operators are trained to capture and remember key details, digital (audio and visual) recordings can capture minute details that may be missed by even the well-trained eye.

6.6 Safety Concerns and Benefits

For any enhancement or augmentation, safety is a critical issue. A known challenge of these technologies is that their cognitive and physical effects cannot be fully known a priori. The study group acknowledges the role the DOD must have in supporting rigorous science in these domains to validate the usefulness of the technologies and to identify and prevent their short- and long-term harmful effects. Although measures are taken to ensure the highest level of safety for the end user, because each human's physiology is slightly different, unforeseen side effects can be expected. The general understanding is that DOD personnel, especially those at the "tip of the spear" (e.g., special operations forces), are prone to seek an advantage over adversaries, even if the chosen technology has not been fully shown to be effective or non-hazardous (e.g., the use of dietary supplements by the U.S. Special Operations Command). Although purely speculative at this stage of development, the early adoption of low-technology readiness level enhancements to keep up with enhanced adversaries may prove an area of concern in the future. Given the particular nature of DOD needs and applications, it is likely that many of these enhancements will be unique to the DOD. Therefore, collection and accrual of data to validate the utility and establish the safety of these technologies may be more difficult than in the civilian sector, in which there are more opportunities to collect data or conduct studies with sufficient sample size. It must also be considered that the long-term side effects will be unique to each augmentation. The remapping of neural networks due to an implant will be vastly different than the muscular implants used to receive optogenetic stimulation. Each implant type, location, and mode of action will carry its own safety and regulatory concerns.

Human enhancement and augmentation would be implemented as a viable technology in DOD personnel for the sole purpose of adding a competitive edge to warfighters to improve their survivability. Each of the technologies discussed here and at the Man–Machine Interface Meeting have the potential to offer improved situational awareness through (1) enhanced sensory perception; (2) streamlined interaction with assets such as UAVs and sensors; and (3) improved communication between squad members, which would directly translate into improved warfighter performance and safety through "left-of-bang" type approaches. Notwithstanding that these examples provide more tangible and predictable safety enhancements, secondary benefits could be possible, based on current understanding of neural plasticity and overall brain function. For example, studies of Alzheimer's dementia have shown that early and frequent brain stimulation lead to reduced plaque formation in aging populations.[32] Although not confirmed, it is possible that enhancements that rely on neural implants or other methods of brain stimulation may increase overall brain activity, leading to slowed aging of neural pathways and long-term benefits to individuals with these types of enhancements. Another consideration and potential safety enhancement is that many of these technologies will incorporate some sort of biometric log to ensure the stability of the implant. These logs could allow for numerous biomarkers to be monitored, which could lead to early recognition not only of implant degradation and failure but also other disease states or conditions that the recipient may experience or develop during his lifetime. By revealing actionable medical information that would not otherwise be detected, circumstances in which enhancements provide safety benefits to an individual may be established.

6.7 Long-Term Effects

Enhancement technologies may be intimately integrated within the human body and enable decades of exchange information with the human nervous system. The long-term effects on the human body and cognitive or psychological functions cannot be wholly foreseen, and therefore, these will need to be determined through rigorous prospective studies. It is anticipated that once these technologies are shown to be effective and safe in the short term, initial deployment would likely be in small specialized teams that are extensively monitored for years during and after military service. These specialized teams could serve as “probe cohorts” to enable ongoing evaluation of benefits, burdens, and potential harms incurred by such interventions. Although the targets will be ever-evolving, some of the questions and concerns that will need to be addressed are discussed below.

Many of the enhancements and implants discussed in this report (case studies 1–4) and on the horizon for the year 2050 and beyond will require a significantly deepened understanding of the brain and how technologies that affect its structures and functions may be engineered. Moreover, it is likely that the specific technologies discussed in each of the case studies will require a neural component or implant to allow for efficient utilization. This will need a massive two-way data feed to and from the brain, as methods and techniques are iteratively developed to “learn” proper placement of implants and accommodate the vast types and amounts of data that are required to sustain optimal functioning of these technologies. How the use of integrated technologies will affect existing brain architectures and functions is not yet known and arguably, can only be known by implementing the particular interventions. In addition, several of the implants pertain to enhanced sensory capabilities. How the brain processes this information and whether it adapts to the new inputs will impact significant areas of future study. For example, augmentation of individual senses may have secondary consequences for multisensory integration and motor coordination. To contend with these, augmentations must be designed appropriately[33] so that displays of information can be digested by the human brain without causing spatial disorientation, negative impacts on coordination, and disequilibrium; these conditions can lead to nausea and sickness. Furthermore, if these data streams show any potential for corruption or miscommunication, improper sensory relay and interpretation could possibly lead to poor or incorrect decision-making by the operator. An example of this could be false identification of targets leading to friendly fire. Would this lead to a “my implant made me do it” type defense in which technology is blamed for such actions and mistakes?

With age, the tissues, integrity, and functions of the human body change in relative capability, plasticity, and sustainability. At present, it is unknown how implants will change the rate, extent, and effects of aging and the influence and manifestations of the implants over time. The possibility exists that the body will lose its ability to interact with the implant as neural connections degrade or muscles and connective tissues change or atrophy. Will an individual who receives these enhancements during his or her service years become even more infirm later in life as the body and implant age? Can enhancements be recalibrated as the body ages to restore functionality or at least ensure operability at some basal level? Or, will the technology provide some measure of protection against or mitigation of the effects of aging, and thereby render the enhanced individual with durable capabilities?

6.8 Active Military Considerations

Integration of enhanced troops into warfighter populations is projected to increase in frequency as we approach the year 2050, and these populations will persist for extended periods of service. This "new normal" will require changes in the way the DOD recruits, trains, deploys, and protects troops and systems under its control. At present, all soldiers and support personnel constitute a significant investment by the DOD. This, of course, is not just an investment in equipment and training, but also in in-service and long-term post-service care. The total life-cycle cost in enhanced personnel will require a change in the way the various branches of the DOD organize and position individuals in their command. Does this create new quid pro quo service criteria? For instance, should the DOD mandate substantially longer commitments of service for enhanced individuals if the DOD is required to maintain these implants in perpetuity? Should all enlistees be eligible for enhancement, or should only very select groups be eligible (e.g., those who are able to meet certain physical and mental criteria)? Can individuals with pre-existing augmentations join the military? How do enhanced individuals rank compared with the non-enhanced, and how does this change the current hierarchies and criteria for promotion and recognition or awards? These questions and others will require serious attention by each service branch as it adapts to the idea of the new normal. Key aspects of these issues are addressed in the next section.

6.9 Integration of Enhanced Soldiers into Active Duty Forces

Whereas human/machine enhancements could potentially increase operational effectiveness of military units, the technologies and techniques to employ them will require study and optimization. These adjustments to current practices will not simply be how we handle personnel but also how we organize enhanced personnel into existing hierarchies, how we utilize them on the battlefield, and how the rules of warfare may need to be modified to accommodate the use and prevent the misuse of enhancement technologies.

Classifying military personnel as enhanced or non-enhanced would add another level of categorization to military status, fitness for duty, and rank that will have to be considered. Enhancement will effectively change the capabilities and professional status of active duty soldiers. In addition, policies and procedures that take into account how these new capabilities will impact the professional qualifications will have to be established, and military occupational specialties will have to be assigned. Present-day military personnel are able to take courses or receive training to further their career and potential for advancement. Is there a future in which obtaining an augmentation conveys an equivalent benefit to an individual's career path? In contrast, could an enhancement limit this potential? For example, what if the enhancement is so unit- or task-specific (i.e., targeting, reconnaissance, etc.) or necessary that it constrains or restricts an individual from being promoted or from receiving a different enhancement that is not compatible?

In the early stages of development and deployment, it is unlikely that individuals augmented through use of invasive procedures will be assimilated into the general population of troops. Deployment of mixed populations will require changes in doctrine, organization, training, materiel, leadership, education, personnel, and facilities to maximize impact and better achieve the mission. DOD leaders must consider that integrating enhanced and non-enhanced personnel within military units is likely to create an imbalance in capabilities. This will almost certainly incur differences in permissions, treatments, and requirements for long-term sustainment. Consideration should be given as to how this would impact unit cohesion or morale of the military unit and whether and to what extent "super soldier" myths will affect unit performance (positively or adversely). For this reason, the BHPC study group recommends that DOD fund and conduct related psychosocial research as development of these technologies advances.

Finally, current DOD rules of engagement require a human in the loop for lethal actions. As technology blurs the line between system and solider, new policies must be developed to define permissions for when to engage in lethal actions for systems under direct human neural control. Is it sufficient for a single human in control of multiple deployed assets to interpret intelligence independently and decide upon the best course of action? In addition to considering how these technologies will alter our own rules of engagement, decision-makers must also develop methods of understanding our adversaries' capabilities, intentions, and permissions in this area.[34,35]

6.10 Reintegration of Enhanced Soldiers Back into the Civilian Population

An enhanced military cohort will eventually have to return to civilian life, which will require secession planning and institution of transition policies that take into account the unique needs of service members with long-term enhancements. The obligations for long-term care of the individual, the security of the technology, and the capabilities afforded by the technology must be considered for each type of augmentation. Policies will have to be tailored to effectively address each consideration and concern. Whereas a soldier with a prosthetic arm is not expected to return the arm post-service, an individual who can control a UAV (or other BCI device or system) with a neural implant may require different considerations upon retirement from service.

Enhancements designed for military applications will likely enable warfighters to perform at a level greater than the previous or general norm, whether through enhanced hearing, vision, stamina, or cognitive capabilities. As an enhanced individual leaves military service, will the military downgrade or deactivate (demilitarize) the capabilities of an enhancement technology, and if so, what will be the (biopsychosocial) impact upon the individual? Although this would seem obvious for individuals able to interact with complex weapon systems or communications capabilities, what are the protocols established for people with enhanced auditory, optical, or cognitive capabilities? If the brain has developed new neural pathways to interpret and use information from these sources, what happens if and when these systems are diminished or deactivated, and would it be ethical to do so? How would an individual be psychologically and socially affected when a physical enhancement, such as strength or stamina due to a boost-limb or exoskeleton, is removed? The BHPC study group recognized the possibility of "post-enhancement distress syndrome" (PEDS), of feelings of inferiority or withdrawal, or even a form of depression could be associated with the non-enhanced state.[36,37]

However, it is important to consider what it will mean for enhanced individuals to "return to normal". An individual re-entering civilian life with enhanced limbs that allow for increased strength or stamina, an eye that provides infrared and ultraviolet vision, an auditory device that provides ultra- and subsonic hearing, or a neural device that optimizes cognitive capability would have a defined competitive advantage over non-enhanced individuals in society. Given the competitive edge imparted to the individual, will there be a propensity for bias in favor of or against the enhanced population? Would enhanced individuals be "throttled" when returned to normal levels? Who determines what these levels should be? Will these enhancements be "reverse dual-used" in the civilian population for personal performance optimization, or as "neuro-corrective" measures for certain types of behaviors? Policies and protections must be established to ensure the sound treatment of vulnerable populations and those who have received enhancing interventions.[28]

The possibility of post-enhancement mental health disorders must be monitored for many years, but what about those individuals who are able to maintain their implants post-service? Granted a prosthetic limb or eye would not be removed when an individual leaves the DOD, but what would policy dictate for long-term maintenance and care of such and other indwelling enhancements (e.g., auditory, visual, or cerebral implants)? All aspects of this question must be considered. When would the military's commitment to taking care of the individual be an obligation to sustain the enhancement system itself? How would this kind of specialized care and sustainment be coordinated with the Department of Veterans Affairs? It must be assumed that technology will continue to improve upon existing and valuable enhancements. Although it is highly unlikely that a veteran would receive an improved "upgrade" post-service, what if such an upgrade maintains functionality, prevents degradation, and provides comfort? What if the original system becomes obsolete? Would technological obsolescence due to lack of an upgrade or the occurrence of PEDS constitute a compensable disability?

In the scenarios that are described, all of the enhancements involve a degree of permanence. The BHPC study group recommended, wherever possible, development of enhancement technologies that can easily be donned or doffed. However, the group acknowledged that this may not be feasible in the near future for certain enhancements. The possession and security of the enhancement technology becomes an issue during, and especially, after military service. For example, if an individual possesses a technology that is not currently available, or if the technology is vastly superior to what is available in other nations, could the individual travel abroad without posing a security risk? What restrictions could reasonably and ethically be placed on someone who has received an enhancement that cannot be removed? To what extent could or should the DOD restrict the individual's movements and track the device's location? Present-day policies are not in place to deal with these questions, issues, and problems.

6.11 Ethical Considerations

At all stages, ethical considerations must be at the forefront of the DOD approach. Landmarks in product life-cycle development, as well as the life cycle of a service member, are the basis for a discussion on ELSI issues. For example, the R&D stage of product development raises unique considerations and invokes existing ethical and regulatory structures for research, including the Belmont principles of autonomy, beneficence, and justice, which DOD investments must satisfy. Likewise, the needs of a service member and DOD responsibilities to him change throughout the course of the individual's military career and post-military life; each stage merits a discussion of ethical considerations.

Principles and frameworks appropriate to one life-cycle stage (either of the product or the individual) will not necessarily apply to another. For instance, DOD-supported research has stringent requirements for voluntariness and informed consent. Thus, a service member who receives an investigational enhancement as part of a study must be fully informed of any known risks and benefits. The individual must agree to participate without undue influence. As technology matures and leaves the investigational stage, the interventions that are part of clinical care (i.e., interventions used to prevent, treat, or rehabilitate injury) would also be judged under existing codes of clinical ethics. However, for enhancements that go beyond clinical care because they are no longer investigational, the ethical and regulatory implications differ. New frameworks and related policies must be established so that ELSI concerns are illuminated and mitigated in a rigorous and systematic fashion. In other words, ethical concepts and tools likely need to be modified or created anew to more precisely address and resolve emerging questions, issues, and dilemmas.

Among the most significant ethical considerations that the study group posited is the issue of voluntariness: under what circumstances, if any, could a service member be compelled to undergo an enhancement that has been fielded (i.e., an enhancement that is no longer in the R&D stage)? Yet even if the acceptance of the enhancement is voluntary, the extreme nature of many enhancements will incur physical as well as mental health effects immediately post-procedure, during military careers, and long-term post service. Can volunteers make an informed decision for new techniques and technologies when mid to long-term effects are unknown?[38] If potential burdens and risks are to be communicated and accepted by individuals who receive such interventions, is the DOD obligated to provide ongoing research into long-term effects as well as care for enhanced individuals?

Therefore, in the spirit of medical (and governmental) non-abandonment, the BHPC study group recommends, as critical, that ongoing efforts to develop biotechnological enhancements must be accompanied by continuity of research to prospectively evaluate the benefits, burdens, and harms incurred by individuals, bystanders, and groups. Clinical care must be extended to individuals who are burdened or harmed by biotechnological enhancements. Toward this end, the study group makes the final recommendations: The DOD should support foundational research (1) to validate human/machine fusion technologies before fielding them and (2) to track long-term safety and impact of these technologies on individuals and groups.

The benefits afforded by human/machine fusions will be significant and will have positive impacts on the human quality of life through restoration of functionality lost due to illness or injury. The military community will also see capability opportunities that will impact operations and training. As these technologies evolve, it is vital that the scientific and engineering communities move cautiously to maximize their potential with a focus on safety. Commensurate investments in these areas will work to mitigate misuse or unintended consequences of the technologies.

Augmentations and enhancements have the potential to impart significant advantages to an individual, and the BHPC study group anticipates costs to national security if the DOD fails to pursue these advantages for the warfighter. The study group expects that the DOD use of enhancements will be intended and designed to provide a competitive edge to an individual's physical or cognitive performance. The use of enhancements will have, partly by design and partly as a consequence, an impact on other individuals and groups besides the enhanced service member. A thorough approach to anticipating, considering, and mitigating ELSI concerns must involve deliberate assessment of the impact on other stakeholders, including bystanders, non-military users, organizations, non-combatants, and other nations. Myriad specific themes or ethical parameters must also be examined systematically, to include unanticipated military uses, changing ethical standards, philosophical and religious beliefs, and opportunity costs.[39] It will be important for the DOD and its partners to commit to advancing ethical precepts and guidelines that account for different stakeholders and ethical parameters with an obligation to care for those who have served at the forefront.[40]

In conclusion, this study makes it clear that the benefits afforded by human/machine fusions will be significant and will have a positive impact on humans through the restoration of functionality lost due to illness or injury. The defense community will also realize capability opportunities that will impact military operations and training. As these technologies evolve, it is vital that the scientific and engineering communities move cautiously to maximize potential with a focus on the safety of U.S. society. Commensurate investments in programs that support the safety and security of cyborg-enhanced individuals will work to mitigate the misuse or unintended consequences of these technologies.

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ACRONYMS AND ABBREVIATIONS

BCI	brain–computer interfacing
BHPC	Biotechnologies for Health and Human Performance Council
ELSI	ethical, legal, and societal implication
PEDS	post-enhancement distress syndrome
R&D	research and development
UAV	unmanned aerial vehicle
UMV	unmanned marine vehicle
USV	unmanned surface vehicle

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