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Cyborg Technology in Bio Engineering: Enabling Technologies, Implications, Applications and Future Trends

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Abstract:
Medical technology has made notable progress in recent decades with the assistance of engineering and information and communication technology. With the aid of miniaturized electronic devices with intelligence and communication capabilities can be used to monitor patients and older people remotely and streamline all the healthcare services required in times of need with minimum human interventions. The advances made in the field of microelectronics have enabled us to manufacture devices that are small enough to be embedded within the human body. When a human being is fitted with a device for the purpose of assisting an underperforming organ or to enhance some biological function, he is known as a cyborg. Cyborg is a portmanteau of two words cybernetics and organism where a biological organism is embedded (or fitted) with some machine elements for the purpose of enhancing some of its biological functions. In this article, the authors take a critical look at cyborgs from different angles with the view of understanding the implications of this technology at individual and social levels along with giving their own interpretations and comments. As this article looks at cyborg technology from multiple directions, it will be a useful reference for anybody who is willing to embark on this fascinating research area.

Keywords: Artificial limbs and implants; Bio engineering; Cyborg technology; Ethical and social implications.

1. INTRODUCTION

Medical technology has made notable progress in recent times through the adoption of information and communication technology into its research with the objective of providing better healthcare to people. Internet of Things (IoT) fitted with advanced sensors enable health practitioners to constantly monitor patients' health and alert the right professionals and other required services including emergency services automatically without human interventions streamlining all the required medical processes increasing the patients' access healthcare services. Recent advances in mobile technology especially the arrival of smart phones empower patients to actively participate in their own healthcare related activities including fitness and health monitoring. All these developments have created ways for a more personalized type of healthcare providing tailor-made and individualized solutions to suit each patient's needs and situation.

Creation of Cybernetic Organisms or cyborgs has been the scientists' longtime dream (1). A cyborg is a part animal(plant) and a part machine whose biological functions are artificially enhanced enabling them to survive in a hostile environment such as space. The technology that makes cyborgs possible in real life is now known as cyborg technology. Cyborg technology has been defined by the leading researchers in this field as "technology that is integrated into the human body and that not only restores lost functions but also enhances the anatomical, physiological and informational capabilities of the body" (2). Cyborg technology and devices are broadly specified into medical implants from pacemakers to brain implants. Another common term used in this field is "cyborg prosthesis" which refers to artificial body enhancements that provide computational capabilities and function as a feedback system (2). The use of cyborg technology may now facilitate even seriously disabled persons to live normal lives like others overcoming their disabilities (3). In this article, the authors review the cyborg technology in bio engineering from multiple angles such as technology, ethics, social, legal, policy and economics and try to predict what to expect in the area related to artificial limbs and other implants in the future.

This article has been divided into six main sections for making the article properly organized with the objective of increasing readability. Section 1 presents the introduction to the overall article describing the problem at hand along with the organization of the article. Section 2 defines Cybernetic Organism presenting its features and capabilities along with a discussion on its implications in multiple fronts such as ethics, social, legal and policy and economics. Section 3 evaluates similar work carried out by other researchers and published/presented in various journals and conferences. Section 4 presents a discussion on some of the notable real life cyborg implementations and Section 5 presents the possible directions where future cybernetics research may move in. Finally, Section 6, the conclusion of this work provides a brief summary of what is covered in the article.

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The purpose of this review is to assess the existing and anticipated progress in the field, as well as identify the impact and consequences of its developments. This appraisal is very important for carrying out effective research, and for policymaking and practices that seek to advance the integration of cybernetic systems into healthcare and society at large. This review aims to demonstrate the nature of the evolution of cyborg technology and society's involvement in the research as well as the novel domains that needs further exploration. This approach allows researchers to see the gaps that have been missed, use the right strategy in filling the gaps, and improve the quality of innovations in bioengineering and healthcare that are being developed and implemented.

2. CYBERNETIC ORGANISM (CYBORG) TECHNOLOGY

Cybernetics is a term that is commonly used by researchers in diverse fields to denote the study of control and communication within humans, animals, machines, organizations, and society (4). CYBernetic ORGanism or CYBORG (or cyborg) in short is a machine enhanced natural organism including human beings and animals (5-7). For achieving certain specific tasks in which the human capabilities are not up to the level of expectations, external elements, especially electronic or electromechanical devices can be embedded into human bodies so that those people perform these functions better (8). Sometimes cyborgs are called augmented human beings as certain abilities of that hybrid being are artificially enhanced beyond their natural abilities (9). Cyborgs are sometimes mistaken with other terms such as robots, android, humanoid etc. Though they sound similar, technically they are different from cyborgs (10). Androids and humanoids are essentially robots, but they have certain human like features maybe in appearance and or behavior (10). On the other hand, cyborgs are living creatures (human, animals or plants) with certain of their functions enhanced through mechanical/electrical/electronic means. Table 1 presents a comparison between cyborgs and robots.

Table 1. Comparison between cyborgs and robots.

Cyborgs	Robots	References
Part machine and part living thing (human, animal, bird or plant).	Fully machine (non-living thing).	(8, 10)
A living being with certain functions enhanced through some mechanical/electrical/electronic means.	Powered by artificial intelligence.	(9)
Majority of the functions are biological.	Almost all the functions are electrical, mechanical or combined.	(11)
Designed to enhance certain functions or capabilities.	Designed to perform specific tasks.	(7-9, 11-12)
Complicated interactions with other beings and environment.	Simplified interactions with other similar robots and environment.	(11, 13-15)
Overly complex in nature.	Simple or complex depending on the need.	(11, 13-15)
Can learn and adapt to their environment.	Mostly pre-programmed and lack emotional intelligence.	(11, 13-15)
Function freely.	Can perform only the programmed task.	(11, 13-15)

2.1 Types of Cyborg Technologies

Cyborg technology can be divided into two main parts as restorative cyborg technology and enhancement cyborg technology (16-17). Restorative cyborg technology is concerned with restoring lost or broken limbs, malfunctioning organs and diminished biological functions of human body so that the person fitted with artificial limbs or other gadgets can live a normal life. Examples of restorative cyborg interventions or cyborgization include bionic hands (18-19), leg prostheses (18-19), exoskeletons (18), bionic eyes (19), and cochlear implants (18). Restorative cyborg technology has thus enabled many disabled people to lead normal life. On the other hand, enhancement cyborg technology increases certain functions of a human body beyond the levels of normal human beings. Another similar division of cyborg technology mentioned in the literature is convenient cyborg technology and conditional cyborg technology (17). Convenient cyborg technology is almost same as enhancement cyborg technology where a person alters a part of his body by implanting a technical gadget. Conditional cyborg technology is similar to restorative cyborg technology where a disabled person is fitted with some bionic implant to help him overcome his disability.

2.2 Enabling Technologies in Cyborg Technology

Several technological developments in multiple fields paved the way for the rapid development of cyborg technology in recent years (20). This subsection looks at how these advancements contribute to cyborg technology. One of the most important advances that helped the development of cyborg technology is the progresses made in microelectronics (21). Microelectronics is concerned with designing, developing and manufacturing integrated circuits using very tiny components (21). The typical feature size and the number of components in a typical high-end microchip such as CPUs are less than 5~nm or 0.005~µm and more than 30 billion transistors (22). These developments have enabled large scale systems with multiple functions to be included in a single chip of few square millimeters. Hence, these chips can be inserted and embedded within human bodies with relative ease. The other development within microelectronics that helps cyborg technology is the development micro-electromechanical systems (MEMS) and nano-electromechanical systems (NEMS). A MEMS or NEMS is a tiny integrated device that combines both mechanical and electrical components (23). Typical size

of a MEM device varies from a few micrometers to a few millimeters and a NEM device is less than 100nm. This type of combined device within a single package (device) with electrical and mechanical functions having special power and capabilities can be embedded within the human body under cyborg technology.

The other important development that helped the rapid progress of cyborg technology is the advances made in the field of sensor technology. Sensors are devices that enable monitoring the environment and detect changes in it so that timely actions can be taken (24). These sensors can not only monitor the external environment but also the internal organs of a human body and their functions as well. Body sensor networks are a special set of wireless/wired sensors (25). Advances in sensors include miniaturization in size, more sensitivity, ability to conduct limited amount of processing before transmitting the data, ability to connect with other sensors and system and ability to work collectively as a group. Another development in the field of sensors that is effectively used in cyborg technology is biological sensors (biosensors). Biosensors are made up of a transducer and a biological element such as an enzyme, an antibody or a nucleic acid (26). The biological element interacts with the analyte being assessed and the biological response is converted into an electrical signal by the transducer. Thus, a biosensor embedded within or on a human body can effectively monitor not only body fluids including saliva, sweat, tears, enzymes, even vitamins and other nutrients but also exhaled breadth that contains large amounts of components arising from the lungs, nasal cavities, and have connections to blood. Biosensors provide direct connection to human skin, body movement compliance, fast response, enhanced application, point of care testing, and self-health management without causing harm to human organs (27).

Another notable development that assists cyborg technology is nanotechnology. Sensors developed using nanotechnology and nanomaterials can effectively enhance the capabilities of cyborg technology (28). As nanostructures have a size that is comparable with biomolecules, they enable new ways to measure and detect biology, perturb cells, and treat patients. Hence, nanotechnology-based approaches are able to precisely measure and perturb living systems yielding deep insights into systems biology and therapeutic strategies enabling professionals to practice personalized medicine to suit each patient. All these advances can be readily used within cyborg technology to enhance human functions selectively without disturbing others. Advancements in materials research have also contributed immensely to cyborg technology. When external devices are implanted inside human bodies, the materials in them may react with body fluids and other materials (29). Hence, these devices need to be constructed using special types of material that are inert in the presence of body fluids and withstand other wear and tears.

Recent developments in artificial intelligence and machine learning have given a big boost to cyborg technology enhancing the capabilities of implanted devices (30). Recent advancements in artificial intelligence have happened in many sub-fields including neural networks, expert systems, deep learning, vision, genetic computing etc. (31). All these developments can be readily leveraged to enhance the capabilities of cyborg technology.

2.3 Ethical Implications of Cyborg Technology

Enhancing human capabilities through an external implant raises many ethical questions of doing such interventions (31). Experts from many different professions such as medicine, healthcare, engineering, legal, social, psychology and philosophy as well as media personnel and policy makers have been engaged in a discussion or a debate on the ethical issues of human capability enhancement and/or augmentation through electronic device implanting for a long time (32). The initial debates on the ethics of human enhancement were centered around whether every implant conducted on a human being for improving a certain biological function is therapeutic or an enhancement (16, 33). Therapeutic enhancement of a biological function is similar to restorative cyborgization where an individual wants to enhance the function of an organ that has lost its ability to function as normal or replace an organ/limb with an artificial one. When a person attempts to undergo restorative cyborgization through legal means, it is morally or ethically not right for anybody to oppose it. On the other hand, if a person wants to undergo pure enhancement cyborgization, it needs to be looked at from a different angle considering multiple factors such as social implication, political correctness, economic viability etc.

Ethical considerations related to cyborg technologies can be approached through three different frames or lenses as individual, professional and social (34). Individual ethical considerations relate to the person who wishes to enhance his capabilities for achieving certain life goals of his. Hence, from an ethical point of view, whether to become a cyborg or not is to be decided by the individual himself without any pressure or demand from the society or authorities (35). Professional ethical considerations in cyborg technology concern the codes of ethics that govern medical/healthcare practices (36). Here the professional who has been hired to perform the cyborgization on an individual needs to take the decision of whether to do it or not abiding by his professional code of ethics. Social ethical considerations involve how the altering of someone's capabilities artificially affects society at large (37). Hence, when a cosmetic cyborgization is to be performed, it demands a discussion and a debate at a higher-level scrutiny with wider focus and multiple considerations.

Healthcare professionals, engineers, and other experts involved in the development and implementation of cyborg technologies face their own set of ethical challenges. There are questions around the appropriate use of these technologies, the need to obtain informed consent, and how to balance the potential benefits against the risks (19). Professionals must also grapple with issues of fairness and equity - should these technologies be made available to everyone, or only to those who can afford them? Additionally, there are concerns around the potential for dual-use applications, where these technologies could be misused for purposes beyond their intended medical or personal use, such as in military or law enforcement contexts (19).

2.4 Social Implications of Cyborg Technology

The possibility of enhancing human abilities through artificial means often raises public concern about equality and social impact (8, 38). History has already seen that whenever a new technology arrives and starts to become popular it attracts the attention of the masses inducing apprehension and skepticism among them (39). Initially people take sides for and

against new technology without properly understanding it or its implications for them. Social practices along with cultural norms and ethics particular to that society will play a major role in the decision to accept it or oppose it in its immediate future, as society makes an ensemble of explicit and implicit rules to protect itself based on its beliefs, past experience and history. Dehumanization and loss of jobs along with privacy, security and liability may be parts of the main concerns people have with respect to cyborg technology (40).

Data privacy implications and challenges of cyborg technologies are evident from the fact that many of these cyborg technologies rely on an individual's data to work. For example, brain-computer interface tools gather specific neurological data; if inadequate security measures are developed for data saving, such data may be used maliciously (41). An example is neuroprosthetics which is used by disabled persons. In the case when someone hacks such neuroprosthetics, or uses them inappropriately, it will result not only in an unauthorized interference with a person, but with their thoughts and actions as well (42). Such breaches also show that the incorporation of personal data into the physical body leaves one's data very compromised. The risks associated with privacy invasion through data leaks are substantial in cyborg technologies. If sensitive data from devices like BCIs were leaked due to inadequate security measures or malicious attacks, it could result in severe consequences for individuals—including identity theft or unauthorized surveillance (41). These risks necessitate robust security protocols and regulatory oversight.

With these cyborg integration, novel autonomy, questions of power and decision making are brought up. In some cases, users can easily be trapped into dilemma in which they lack adequate information on how their data is handled or how their augmented abilities perform (43). For example, where an implantable device is used for cognitive enhancement but the user has no clear understanding of how it operates or its implications and effects, the person might inadvertently sacrifice control of his or her thoughts (44). This scenario highlights why, there is a need to set appropriate protocols that enable users understand what they are consenting to. The psychological effects related to cyborg technologies help to create an understanding of various changes in mental health. Such feelings make some people develop identity crises or feel incompetent when they are compared to other people who may not use such technologies (45). In addition, the concern created by society about acceptance or the rejection of dehumanization process can worsen the mental health conditions among the users (46). Given the trend of increased cyborg adoption, such psychological implications must be grasped to build adequate infrastructures for the users.

Users currently face dilemmas regarding their reliance on cyborg technologies versus traditional methods. For instance, while some may embrace enhancements for improved performance or quality of life, others might struggle with ethical implications or fear societal rejection (47). This internal conflict can lead users to question their choices constantly whether they are enhancing their lives or compromising their humanity. In order to alleviate the fears and apprehension of people about cyborg technology, more awareness campaigns including short films, seminars, commercials would be needed to highlight the benefits of them as well as professionals promoting the cyborg technology among the masses should be able to answer any question raised by them on perceived risks. Regulatory bodies such as the FDA in the USA and various EU agencies are beginning to address these concerns by establishing guidelines for cyborg technologies' development and use. However, there remains a gap between rapid technological advancement and regulatory frameworks designed to protect users' rights and privacy (42). Continuous dialogue between technologists, ethicists, regulators, and users is crucial for creating effective policies that ensure safety while fostering innovation.

Almahameed *et al*. (48) have conducted an experiment using a cyborg ophthalmologist. The results of this experiment show that users are ready to accept the services of a cyborg surgeon based on multiple factors. Out of the factors influencing the user acceptance of the services of a cyborg professional, social influence played a leading role in the final decision to accept the services of a cyborg surgeon. Researchers have opined that individuals tend to make their own decisions based on other individuals' suggestions and recommendations, especially when the product, technology or service is new, and the outcomes are not well known. This is mainly due to the fact that human beings are inherently social creatures who rely on one another for both survival and for thriving in life.

Pelegrín-Borondo *et al*. (35), Gauttier *et al*. (49) and Racine *et al.* (50) have all analyzed the implications of artificial cognitive enhancements on society in their works respectively. They have raised some important questions about human cognitive enhancements. They mainly focus on three specific questions as arguments which are 1) Significance of psychological and social outcomes of cognitive enhancement; 2) Equivalence of different methods of cognitive enhancement; and 3) Agent (cognitive enhancement user) motivations. This article stresses the need to find answers to these issues and treat them separately. The study presents arguments of both supporting and opposing parties as additional information along with methodological and conceptual challenges in finding suitable answers. As a help to future researchers, the authors of this paper have also mentioned possible studies that can be undertaken to find answers. Thus, Racine *et al*. (50) have only touched on the issue of ethical and social issues that may arise as a consequence of cognitive enhancements and stopped short of providing answers to the questions they themselves have raised.

Alongside that, as stated by Gauttier *et al.* (49) raised the issue of inequality that may arise in a society as only some people opting to enhance their cognitive powers. This is a valid and relevant question that needs answers from society's point of view. In answering this question, author states that whatever the claim that is there in society now doesn't have any empirical evidence to support it (49). The study further states that artificial cognitive enhancements can be embraced wholeheartedly for three specific reasons including 1) There is no concrete empirical evidence that the availability of facilities for cognitive enhancements will lead to inequality in society; 2) Even if cognitive enhancements lead to social inequality, the advantages that can be achieved through cognitive enhancements will outweigh the shortcomings; and 3) Even if cognitive enhancements will lead the substantial inequalities in society, prohibition will not be the right answer to this problem.

Based on the other evidence and arguments, the study concludes that policy makers should try not to prohibit human cognitive enhancements. Rather try to minimize the social problems that may be caused through other proactive measures. History has shown that any new technology or a paradigm change would initially lead to some inequality in society as everybody would not be in a position to take advantage of those technologies or paradigms. But with time, any technology

will become a commodity that majority in the society would be able to take advantage of it. There is ample evidence that both industrial revolution in the 18th century as well as the information revolution created by the invention of computers created a social inequality initially, but today we can see that fruits of both these revolutions have reached majority of the masses.

2.5 Legal and Policy Implications of Cyborg Technology

From history, it is amply evident that any new technology has been exploited by the rich and those in power to their advantages (51). Hence, those in power should step in to protect the underprivileged and poor through the enactment of laws and policies. Crootof (52) has highlighted the fact that there are fundamental differences between the ways humans and machines process information or reaching conclusions. Hence, she opines that the policy makers should not rush into enacting laws covering both humans and machines especially cyborgs equally.

Colasanti (53) has analyzed issue of cyborgs in the light of American Disability Act and the Assistive Technology Act. That study has shown how these acts can be creatively interpreted to accommodate technologically enhanced persons within the normal society. The study also opines that the judiciary needs to be more creative and needs training in interpreting laws in the future. Throughout the discussion, cyborgs are treated as disabled people rather than enhanced or augmented humans. This is a shortcoming of the argument of as now cyborgs have more abilities than normal human beings rather than disabled ones. The study does not discuss the most important issue of misusing the newly acquired or enhanced abilities by the cyborg itself or a third party. Hence, authors of this paper are of the opinion that more intellectual debate is needed in treating the cyborgs as super (augmented) humans rather than disabled people.

Quigley and Ayihongbe (54) have raised the pertinent questions that need to be answered by both law makers as well practitioners of law. The main questions they raise are given below.

- Is the device implanted inside a person to be considered as a part of that person like natural limbs and other organs or as an object?
- When an implanted device is damaged by a third party, should it be considered as a personal injury or damage to property?
- Who is responsible for the working of the software included in the implanted device?
- How should the law deal with when a third party accesses an implanted device either legally or illegally?

The current laws and regulations are inadequate to answer the above questions and hence it is required to re-analyze the conceptual and philosophical underpinnings of the law and the law itself (54). In order to answer these questions, they have analyzed the challenges posed by the cyborgs to the law from five different angles including medical device regulation, safety, and product liability, damage to devices and liability, data and privacy, security and biohacking as well as intellectual property rights. The study concludes that in order to meet the challenges brought about by advances in technology, the law must reorient itself starting from the lowest levels of legal philosophy itself rather than making some superficial changes to the practice of law and decision making.

Morozov *et al*. (2) and Castell (55) have presented an in-depth discussion and analysis on different laws enacted covering cyborg technologies across different countries of the world. The researchers have highlighted the fact that while some countries have already started legislating to streamline cyborg technology, others are still debating about the ethical issues of augmenting human capabilities through artificial means. Researchers have shown that in many jurisdictions, prostheses and implants are regulated as medical products to ensure public safety. Researchers have also shown that certain parts of cyborg devices can be protected using the existing laws of copyright law, patent protection law, intellectual property law etc. On the other hand, users or customers can be protected using laws enacted for public safety.

For instance, cases that involve medical devices usually set precedent as far as responsibility for products that fail, or harm are concerned (54). As illustrated by a case concerning a faulty pacemaker, courts decided whether damages are personae injuries or damage to property, which was applicable to subsequent cases concerning implanted devices (56). We have seen such precedents as arguing for the continuous legal discussion as courts seek to define the rights and duties concerning the enhanced individuals. Also, recent decisions concerning data loss, specifically pertaining to health information, show how the courts might respond to privacy issues arising from cyborg technologies (57). These cases show that the law that surrounds IT must grow as such technology develops so that the rights of the individual can be protected while at the same time creativity can be encouraged.

An ethical framework regarding cyborg technology must focus on human rights and adjustment polices to such technologies. This framework should respect autonomy, the concept of informed consent, privacy and non-discrimination and equality on use of enhancements (44). These ethical considerations must be recognized by policymakers to enable them to advance or widen the gaps of the currently existing social inequalities to see that those who are marginalized are not left behind as more enhancements come into market. Legal policies governing the use of the technologies must include ethical consideration through the legal consent processes these users may undergo; to see they fully understand the risks and benefits of any enhancement before they proceed to have it done to them (41). Finally, as the concept of cyborg technology progresses at a fast pace, it is only fitting that the law that governs IT follows this pace. In policy making, these steps mean that any proposed legislation concerning these transformative technologies will strive to pursue ethical goals and thus meet with less resistance from the legal system, by reference to the relevant case law. Stakeholder involvement will be critical in ensuring adequate consideration of disciplinary solutions that will uphold the rights to technology.

Therefore, the experts in this field including the researchers, technologists, law makers and law practitioners should come together start a debate with the view of coming up with a suitable set of laws to regulate the industry as well as protect the rights of the stakeholders including general public. Also, the legal practitioners including judges and lawyers need to be provided with training on how to deal with situations and environments that include human beings, augmented human beings and machines thinking and behaving like human beings.

2.6 Economic Implications of Cyborg Technology

Similar to any other technology, cyborg technology also envisages improving the efficiency and productivity of human beings through human capability enhancement (58). Already robots have been used in many jobs that are either difficult for human workers to perform or for efficiency reasons (59-60). There are three main arguments about robots in society (61): 1) Robots are taking people's jobs; 2) From manufacturing, robots are now making inroads into other areas like driving, logistics, and inventory management; and 3) Despite negative effects, robots increase productivity, lower production costs, and in turn create new jobs.

Similar arguments were there about machines and vehicles during the 1st and 2nd industrial revolutions too (62-63). But with time, several positive things happened due to the mechanization of many jobs. Due to mechanization, cost of production reduced, productivity increased, and quality of products improved etc. (64). Also, mechanization created new jobs including machine operators, technicians, drivers, machine designers and manufacturers etc. (65). Similar to this one, though robots are replacing human workers from certain types of jobs, there are many positive effects of using robots in place of human workers. The following are some of the positive effects of employing robots to do routine jobs instead of human workers.

However, there is no projection on market growth or financial trends in demand for cyborg technology over the last five years. This absence of data poses problems in the overall evaluation of the economic consequences of cyborg technologies. Since the progresses that went forward and the broad range of industries these technologies are already being used in diverse areas such as healthcare, manufacturing, and logistics, there is a need to perform a detailed market analysis on the future growth and probable financial effects. With increased productivity across multiple sectors and industries, it will result in an increase in gross domestic product (GDP) across the entire country. The study carried by Graetz and Michaels on the effects of robots in the economy using data collected from 17 countries over a period of 15 years found that on average, across the 17 countries, the increasing use of industrial robots over the time period raised the annual growth of GDP by 0.36% (66). They compared this substantial growth to the boosts in productivity that occurred at the turn of the 20th century from steam technology that powered the 1st industrial revolution.

Robots are in fact creating new, high-salaried jobs that require skilled workers (67). While robots are replacing low-skilled workers and automating the tasks that they perform, robots and automation again create higher-value work that demand workers higher qualifications and skills. For example, in manufacturing, robots can perform lower-level routine tasks on a factory floor while highly skilled knowledge workers work in the laboratories and design offices that demand higher levels of cognitive skills. In their report in the year 2020, the World Economic Forum estimated that there would always be new jobs as robotics advancement continued and it was estimated that by 2025, 97 million fresh jobs would be available, and these include jobs within automation sector in development of data analysis, artificial intelligence and robotic maintenance among others (68). Also, on average, for each robot utilized in manufacturing a firm generates 1.6 new jobs elsewhere to meet the resultant demand for the more efficiently produced outputs (14).

Similar to the revolution brought in by robots in industry, it is now time for cyborgs to create their own industrial revolution. There are many situations where people would like to interact with a human being rather than a machine, even if the machine is more sophisticated or looks like a human being (69). This is the right place for cyborgs to thrive as they have the right combination including the biological qualities of human beings while the skills required for the job have been enhanced through technology. There have been multiple studies conducted on the performance of cyborgs as front-line employees where they have to interact with customers constantly as part of their job function (58, 70). All these studies prove that cyborgs will be able to perform better than their human or robot peers. Also, cyborg technology will be able to bring disabled people, another marginalized sectors in the society back to work (71). Hence it is safe to conclude that cyborg technology would have a positive economic impact as a whole.

3. RELATED WORK

Many researchers have published or presented reviews of cyborg technology analyzing the capabilities and limitations of this technology in journals and conferences respectively. This section takes a critical look at these works with a view to explaining the work presented in this article is different from them all. Table 2 presents the summary of the related work with respect to strengths and weaknesses and a brief discussion on each article is presented thereafter.

Oyebola and Oluwaseun (72) have presented an educative note on cyborg technology. This is a brief note prepared with the objective of introducing the concept of cyborgs. This note covers the social, ethical, legal or economic aspects of cyborgs in real life. When discussing multiple aspects of cyborg, the authors lose their focus and fail to distinguish the real-world implementations from imaginary presentations such as cyborgs in movies. Also, there is no mention of the technologies that make cyborgs possible in real life.

Priya and Revathy (73) have presented a brief overview of cyborg technology, touching a few aspects at the surface level. The references used in this work are old and hence none of the recent developments in this field is discussed or there is no mention of the enabling technologies that made this promising technology possible. The review presented by Dhandapani (17) is also similar to Priya and Revathy (73) work. This is a very surface level review touching only a few technical aspects of cyborg technology. The references are not only older than the resources mentioned in Farbak and Plasienková (6), but most of the references are website-based that had not undergone any peer review. The review presented by Keer and Khan (74) is also very shallow similar to Priya and Revathy (73) and Dhandapani (17). Barfield *et al.* (75) have presented comprehensive work on cyborgs and enhancement technology. Though it is a comprehensive work, the scope of this work is very narrow discussing only about different enhancement technologies or possibilities. Hence this is a review of enhancements rather than that of cyborgs or their applications.

From the above discussion and the summary in Table 2, no comprehensive work analyzing cyborg technology from different aspects is available in the literature. This is a huge gap as new researchers who are planning to start their work

in this promising area need to access multiple sources before they can decide on proceeding further. This paper expects to fill that gap as the initial reading material for any interested researcher in this field. In addition to the information presented in this paper, there is a huge collection of related literature listed in the reference that can be used by any interested reader to explore the subject in more detail.

Table 2. Summary of related work on cyborgs.

Work	Description	Limitations
(72)	A brief educative note trying to introduce the concept of cyborgs in real life. The review lacks in many aspects including the implication of cyborgs on personal and social life of people, enabling technologies that make cyborgs possible in real life etc.	Lack of distinction from real world implementations from imaginary presentations.
(73)	A brief overview touching some of the aspects at surface level. Incredibly old references and hence the developments in the field are not touched.	Surface level discussion and lack of current and credible references.
(75)	Scope is very narrow as the authors discuss only about different enhancements that are made possible through cyborg technologies.	Fails to address restorative cyborg technology.
(17)	Very shallow work. References are mainly web sites and hence the quality of the information cannot be guaranteed.	Surface level discussion and lack of current and credible references.
(74)	Very shallow work based on information published in unauthentic sources such as news articles, websites and Facebook.	Superficial discussion on enabling technologies and lack of current and credible references.

4. APPLICATION OF CYBORG TECHNOLOGY ON DIFFERENT SPECIES

Several real-world cyborg implementations have been reported in the literature. This section takes a detailed look at these works for understanding the implementation details as well as their impacts. One of the cyborg implementations that has attracted a lot of attention is that of Neil Harbisson (76). Neil Harbisson (a Spanish artist) was born color blind and hence could see nothing but shades of gray. Neil Harbisson was implanted with an antenna called an ‘eye-orb’ permanently to his skull that connects to his brain. This eye-orb vibrates differentially on seeing different colors that are transmitted to a chip embedded on his head closer to the brain enabling him to feel (or hear) different colors. This eye-orb has made Neil Harbisson more than a human being as he could now recognize (feel or hear) colors that are beyond the natural vision of human beings (41, 48). Other human beings known to have implanted microchips in their bodies include Moon Ribas for detecting earth vibrations leading to earthquakes, Liviu Babitz for sensing vibrations when facing the north pole or sending and receiving data and Rich Lee for listening to music without headphones and for detecting magnetic fields and radiation (77,78).

Valeriani *et al*. (79) have reported the integration of a residual neural network (ResNet) through a brain-computer interface to a human participant for improving his decision-making powers. In this experiment, human participants and ResNet were employed on that same face-recognition task and brain computer interfaces were used to decode the decision confidence of human participants from their encephalography (EEG) signals. Different types of cyborg groups consisting of humans with and without the interface, groups of humans with ResNet and RestNet alone had been employed in the task with the objective of comparing results across different groups. At the end of the experiment, it was found that the cyborgs of combined forms of humans and ResNet could achieve significantly higher accurate (35%) results than ResNet or average individuals or a group of humans alone on their own. These results clearly show that enhancing the power of human beings with the aid of technology could achieve better results than either through natural capabilities or technological means (gadgets) alone.

Yang *et al*. have created a cyborg-moth (80) by connecting a wireless microchip with four micro ultraviolet LEDs on the back of a live moth (80). The main objective of the design and building of this cyborg was to carry out UV ray stimulation to control its flight in a three-dimensional (3D) space. The control model outputs seven flight parameters in order to fully manage the flight of the moth in terms of direction, velocity and acceleration. The proposed model incorporates a fuzzy deep learning model for learning common behaviors, group-specific behaviors, and individual-specific behaviors to achieve a high control success rate. The control is implemented using two units as behavior learner and a control learner where the behavior learner enables the system to learn how UV ray stimulation affects the flight behavior of moths and the control learner helps the control to learn how to steer the moth in the 3D space. The experiment results showed that the proposed model is an overwhelming success as they could achieve more than 81% control success rate in flight parameter control. The implementation of this cyborg-moth is significant in the direction of cyborg animals and insect research and applications as this method can be easily extended to other animals. Cyborg animals and insects have applications in many areas including search and rescue, target location, surveillance, animal population control and endangered species protection.

Many researchers have developed cyborg rats for different purposes (81-84). All the researchers have reported that they managed to achieve high levels of success in controlling the rats and the techniques can be easily extended to cover new applications. Similar to rats, other animals like pigeons, moths etc (85-87). Researchers have shown that not only humans and animals can be augmented through cyborg technology but also plants too (74, 88-93). Since it is not possible to insert wires and other electrodes into plants, the researchers have grown nanowires inside the xylem of the plants that are to be later used as touch sensors, motion sensors or antennae depending on the requirements or analog and digital organic electronic circuits and devices manufactured in living plants themselves (88-90). Arya and Pappa (91) have even gone to the extent of controlling the inner mechanisms of plants through electronic means by implanting sensors and actuators within them for increasing the yield and modifying the urban ecosystem. Through these experiments, researchers have shown that plant physiology can be altered externally as they could slightly change the color of the leaves by applying voltage.

In addition to what is presented above, a new field commonly known as animal robotics is now emerging (94-95). Animal robotics Animal robots differ from traditional robots both in structure and principles as they are composed of organic and mechatronic parts and use a bio-machine interface and simulator (96-97). Animal robots have many advantages over traditional ones in terms of energy usage, self-orientation, and natural concealment providing notable theoretical as well as practical values for scientific investigation, community service, military usage etc (98).

5. FUTURE DIRECTIONS OF CYBORG TECHNOLOGY RESEARCH

From the discussion presented above, it can be seen that cyborg technology has many advantages for human beings if used wisely. Hence, research on cyborg technology will not cease in the near future as the advantages of this technology outweigh the disadvantages. There are many application areas where cyborgs can be very helpful compared to using pure robots or humans/animals especially in space exploration, military, undersea explorations, mine exploration etc. Hence, cyborg technology needs to be developed further through extensive research in all the related areas including computing, communications, ergonomics, robotics, artificial intelligence, materials technology and micro/nano electronics.

On the other hand, in addition to technical research the related areas including legal, social and political need to be developed in such a manner that technical developments can be leveraged to human development rather than destruction. If properly applied cyborg is one of the greatest technologies which has very many merits to human beings. New studies on this topic will therefore continue to be carried out in the coming years. This is because there are many application areas where cyborgs can be especially valuable more than robots or humans/animals or both, particularly in space exploration/mission, military uses, underwater exploration/operations and mining. Hence, there is need to advance cyborg technology by using various interdisciplinary research areas.

However, few drawbacks and challenges need to be considered about this technology. The societal ethical and moral implications with regard to the enhancement of human capacities remain a major concern. Living with one's identity and one's autonomy are inherent issues raised by cyborg enhancements and their respective risks elevate societal acceptance (43). In addition, depending on the approach realized in the implementation of cyborg technologies, the situation may worsen the social differentiation because people with limited opportunities will be able to afford cyborg technologies only with the help of additional funds collected from their counterparts.

Another challenge is the technical limitation of cyborgs. Several of these improvements are still in the development stages, others are not implemented due to the high costs involved or regulatory requirements. For example, applications such as brain-computer interfaces (BCIs), which aim to augment/replace cognitive functions, holds lots of potential, however, current safety and effectiveness of these applications have not been fully proven and may still need some enhancements (35). Third, resistance from anthropocentrists towards integration of cyborgs into existing social structures, in favor of more classical human relationships over enhanced beings.

To address the limitations of cyborg technology, the authors of this article propose a multifaceted approach. First, governments should facilitate formation of standard policies and establish frameworks to encourage ethical equitable access to every individual. Secondly, awareness creating campaigns also result in fostering acceptance of such technologies by the virtue of demystifying said technologies and by the gain if information on advantages surrounding the technologies. Third, more joined work by technologists, ethicists, sociologists and policymakers is necessary to construct integrated and effective strategies taking into account the potential of technologies and the overall impact on societies. Fourth, inclusive design practices should confirm that technologies that create cyborg relationships satisfy those requirements of the various populace and are available to the existent minority population. Last but not the least, introducing pilot projects across the spheres of activity can collect data on the performance and social relevance of cyborg technologies to fine-tune the design and real-life application in response to exercises.

Cyborg technology is seen to have potential and benefits to human in different area on one side, and on the other side still has limitations and challenges which need correct consideration taking ethical, technical, and social aspects into account. But it is possible to minimize and mitigate such risks and preconditions of social divides with help of interdisciplinary approach and creation of the adequate regulative policies: let the cyborg technology would become an addition to the human progress rather than the potential source of the ethical problems. More investigations and discourses on this field will be necessary for optimizing the advantages to be derived from the disadvantages of using this revolutionary technology.

6. CONCLUSION

In this paper, the authors presented a comprehensive review of cyborg technology analyzing it from multiple directions. After providing a comprehensive introduction to cyborg technology and enabling technologies that made current advances possible, the discussion delved into the implications of this technology on different aspects of human life including ethics,

social, politics and economics. The paper also presented a brief discussion on similar reviews conducted by other researchers as well as cyborg implementations on humans, animals, insects and plants. In conclusion, the authors are of the strong opinion that cyborg technology is here to stay and will develop further in the future. Though, initially only rich people will be able to benefit from this technology due to high costs, with time it will be commonly available for anybody as the cost of related technologies comes down. With time, therapeutic cyborgization will help people overcome their disabilities that they were born with or acquired later and lead a normal life as any other member of the society. Also, the authors would like to stress the need for the development in other related fields such as legal and policy making to make this technology as widely available as possible to meet the needs of the people and to reduce the negative effects of it.

AUTHORSHIP CONTRIBUTION STATEMENT

Both authors contributed equally for research, writing, editing and revising the article.

DATA AVAILABILITY

Data are available within the article or its supplementary materials.

DECLARATION OF COMPETING INTEREST

Authors declare no conflict of interest with anybody or any organization with respect to the work presented in this article.

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