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Hybrid bionic control system for prostheses: a review

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The legs and hands are the most susceptible to loss and this is due to the fact that they are prominent external organs in the human body. With increasing disasters, accidents, wars and diseases the loss of limbs is increasing, making the individual restricted in freedom and movement and pursuing to find alternatives to improve the individual's life is extremely important. Modern bionic prostheses are the best alternatives to replace amputated ones to perform both aesthetic and functional tasks. On this basis and by analyzing the most common and used methods in prosthetics management as the electroencephalography (EEG), electromyography (EMG), and functional near- infrared spectroscopy (fNIRS) methods, knowing their advantages and disadvantages, comparing them and documenting their results from the outputs of literature and previous experimental studies, whether in individual use or hybrid use.In the light of these data, this article highlights the most common technologies and considers their superiority and insuperiority, which can be suitable for the formation of a hybrid bionic control system for prostheses or rehabilitation and restoration of lost functions. Based on the most important studies that have dealt with these technologies whereas individually or in their hybrid state. In addition, this article provides an encouraging outlook for those interested in scientific research to research, compare, identify and characterise superior hybrid systems related to exoskeletal control systems and in particular prostheses.

Keywords: hybrid bionic control system (HBCS), hybrid brain-computer interface systems HBCI, neural interfaces, electroencephalography (EEG), electromyography (EMG), functional near- infrared spectroscopy (fNIRS), prosthetics.

Introduction

Natural disasters such as earthquakes and other, human disasters such as wars and other, road traffic accidents, diseases and others leave behind a lot of disabilities in various parts of the body. The physiology of the human body is a very complex, however at the same time an ideal and highly organized structural system consisting of dying and regenerating cells that have lethargy but activate that cells work together to perform functions necessary to maintain life. Science has not stood still in the face of these problems, it has touched all the problems that destroy human life to prevent them from occurring or to monitor and diagnose them and then develop appropriate treatment for them. In fact, it is not possible to count human health problems in one study, so this article seeks to focus on the external problems facing humans, especially the external limbs.

The loss of an external limb takes away the beauty of the body's structure, therefore the amputated part must be replaced in order to give the body its strength and beauty. In line with this, prostheses were previously used for decorative and cosmetic purposes, and this is documented by the ancient history in Egypt, where a large artificial toe worn by an Egyptian woman was found made of wood, and that was three thousand years ago [1]. The huge revolution of technological progress that cast a technical shadow, and entered the prosthetic community in its quest to find an alternative system for amputated limbs to improve the lives of amputees.

Modern bionic prostheses have controllable actuators for performing motor tasks. Therefore, a prosthesis can be given another definition as a controllable device that replaces the amputated limb to contribute to the functionality and aesthetic structure that the natural limb had. The history of the development of the first neural interfaces was in 1973-1977 by a research group and has been documented in the scientific literature [2, 3]. Neural interfaces control the devices of artificial limbs and neural interfaces can be defined as a complex of hardware and software for the connection or functional interaction between a biological object (human or animal) and an external machine, that is, for direct communication of computing or other digital intelligent control systems with the brain and the most famous and most commonly used neural interfaces are brain-computer interfaces.

It can also be noted that neural interfaces can be classified depending on the nature of the work, while recent studies have proven the possibility of forming another system of neural interfaces called hybrid brain-computer interface systems, which abbreviated as HBCIs. The function of neural interfaces depends fundamentally:

- ✓ Based on the real-time detection of characteristic wave patterns of brain activity carried out using neuroimaging methods, the most common of which are electroencephalography (EEG), functional magnetic resonance imaging (fMRI), functional near-infrared spectroscopy (fNIRS), etc.
- ✓ Based on the transformation of the information obtained into control commands for devices such as a wheelchair, prosthesis or any exoskeleton, etc.

HBCIs are not limited to single data processing, but are based on hybrid double and triple data processing [4], [5–7]. Neuroimaging methods can be based on BCI or hybrid neural interfaces. Currently, the most prominent and popular methods for controlling neuroprostheses neuro-rehabilitation are EEG [8, 9], fNIRS [10, 11] and electromyography (EMG) [12, 13].

It is known and as documented by recent experimental studies, the most common methods are (EEG, fNIRS and EMG), which are of great interest in the fields of prosthetics. It can be noted that these methods (when used independently) cannot form an integrated system and this is due to

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several inherent disadvantages. However what distinguishes these methods is that they can be one that can fill the shortcomings of the other with which they share in the composition of the hybrid system. On the related hand, fNIRS technique is one of the most important ways to form a hybrid system, as it does not depend on muscle activity, the absence of which, muscle disease or lethargy, causes a deficit in EEG and EMG techniques.

In the light of these data, this article highlights the most common technologies and considers their superiority and insuperiority, which can be suitable for the formation of a hybrid bionic control system HBCS for controlling prostheses based on the most important studies that have dealt with these technologies, both individually and in their hybrid state. In addition, this article encourages those interested in scientific research related to prosthetic control systems, exoskeletons and in general devices that can be controlled through the biological imagination.

Scope of the research methodology strategy

The main aim of the research was to popularize the idea of creating hybrid bionic control systems for prosthetics and to identify the main directions for further discovery and development to achieve this goal, for this it was necessary to consider the following tasks:

- focus on the analysis of literary sources, propose the most important criteria for candidate methods for the creation of the hybrid system;
- evaluate the advantages and disadvantages of the main types of neural interfaces as a hardware-software system when used independently or in a hybrid form;
- identify, study and compare the most common methods within the control frameworks of bionic prostheses;

Since the hybrid system is likely to be a comprehensive and potentially promising system for controlling prostheses, the focus has been on fNIRS technique, which serves as a complementary tool to fill other technical deficiencies. The most important monographs and articles describing current neural interface designs based on various physical principles were selected for analysis. Among a lot of scientific articles and publications, relevant topics have been selected, documented in reputable scientific journals, as well as considered sites such as https://scholar.google.com/ and others. In addition, various links are indicated at https://www.mdpi.com/journal/sensors, https://www.refseek.com, and others.

Finally, some articles were discarded and some others were deleted, and and then the opinion of experts who have an insightful vision that to return to the essence of the topic in order to establish a control system (the subject of the research).

HBCS based on HBCI for controlling prosthetics.

Understanding brain functions is essential for efficient BCI applications, and its development is closely related to physics [14], there are also promising studies that delve into the future development of BCI, such as quantum sensor technology, which has great potential for the development of BCI [15]. The classification of brain states can be performed in real time in accordance with the registered brain activity caused either by spontaneous physiological processes or by external stimulation using an intelligent BCI system. BCIs are usually divided into categories of unidirectional (receiving signals from the brain or sending them to it) and bidirectional (allowing information to be exchanged in both directions), and this depends on the direction of their work [7]. The classification of BCIs in general is given below [1, 16].

- **Control command-based classification** can be classified as: active BCI, reactive BCI and passive BCI
- **Input data processing modality-based classification** can be classified as: synchronous BCI and asynchronous BCI
- **Invasive and noninvasive BCI and Brain-machine interfaces** can be classified as: noninvasive BCI and noninvasive BCI

In the context of a hybridization system, a HBCI can be in three types according to various signals of brain activity:

- **HBCIs** when various reflected signals of brain activity are used.
- **HBCIs** when signals of brain activity in conjunction with external signals of different nature are used.
- **HBCIs** when various physiological brain activity simultaneously with recording technology are used.

It has been confirmed that the performance of individual BCI provides a lower classification accuracy than HBCI. In a related context, one of the main reasons why HBCIs are not widely used is the enormity of their hardware and complexity. To decode this complexity, it is necessary to implement lightweight and compact HBCI with care to reduce performance degradation. In the terminology of hybrid systems, according to the facts of the studies of the qualified technologies and the outputs of the technical mix of these technologies, which leads to an advantage over the individual methods. Therefore, initiating a hybrid system for controlling prosthetic limbs is possible and the proposed system can be referred to as shown in Scheme 1.

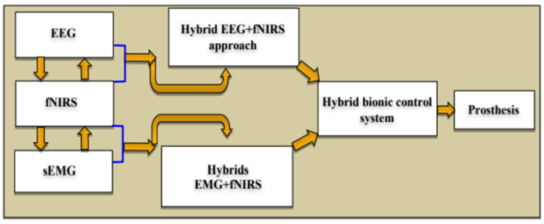

Fig. 1. The scheme of the hybrid bionic control system HBCS

Рис. 1. Схема гибридной бионической системы управления HBCS

It is noted that the hybrid system is not limited to fNIRS technology with other technologies. As there are studies that have used the hybrid system in combination with EEG and EMG techniques [17, 18] as shown in Figure 2. However this system remains unpromising because it depends on muscle activity, which may not be available in all conditions, therefore the design of a control system with fNIRS as in Scheme 1 and may be a promising and comprehensive system for controlling prostheses.

The results of previous studies certainly make it possible to work on finding and installing a hybrid control system for prosthetics. It can be noted that both hybrid systems that share with fNIRS have proven very great successes, as documented in Table 2.

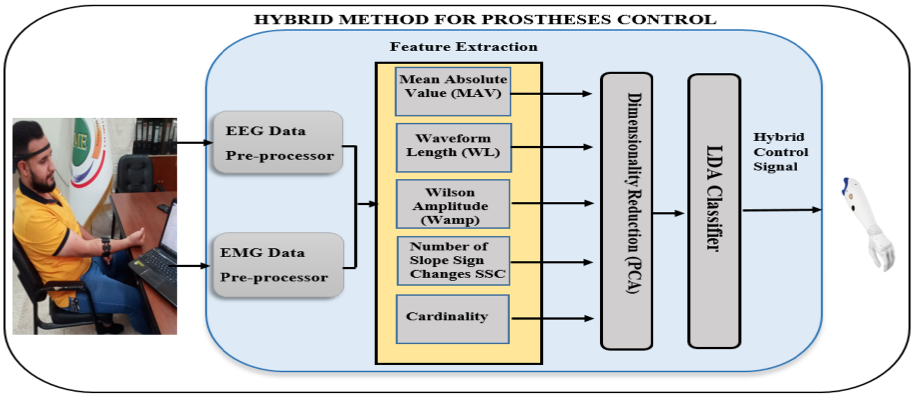

Fig. 2. The hybrid system of EEG and EMG techniques based on muscular activity

Рис. 2. Гибридная система методов ЭЭГ и ЭМГ, основанная на мышечной активности

It is also noted that there is no confirmation that there is a superiority of the hybrid system of fNIRS with EEG over the hybrid system of fNIRS with EMG , and this is a positive indicator that future studies should take into account by comparing these systems and further work to establish HBCS for prostheses and others.

Qualified technologies for the formation of HBCS

The possibility of forming a hybrid system must give superior outputs to the individual system and this is due to the contribution of the systems to each other to fill the shortcomings of the other system to distinguish the hybrid system. Due to the importance of qualified methods, will summarize previous studies that dealt with these methods, whether in their independent or hybrid mode.

Independent mode

EEG

In its invasive state, EEG poses a risk to the patient's life because it requires surgical intervention, i.e. it is implanted inside the body (organism) and this leads to the death of the surrounding or contacting cells as shown in Figure 3 [19], which necessitates its replacement from time to time. In its non-invasive state, it is highly sensitive to artifacts and noise, which is why it has not found application in the field of prosthetics when used individually [14]. EEG technology has the potential to be a complementary tool to other technologies, as it provides a system with high spatial and temporal resolution.

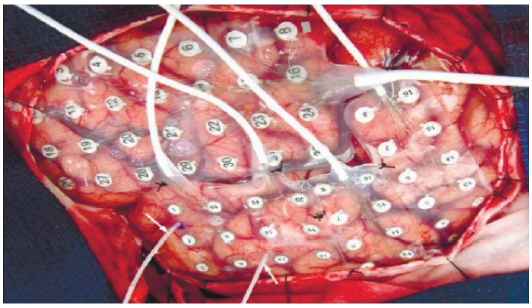

Fig. 3. Shows EEG electrodes implanted on the surface of the brain, noting the direct contact and friction between the cells and the implanted electrodes

Рис. 3. Показаны электроды ЭЭГ, имплантированные на поверхность мозга, отмечен прямой контакт и трение между кнопками и имплантированными электродами

EMG

Electromyography (EMG) is a diagnostic method that carries motor commands during the recording of the electrical activity of bioelectric signals resulting from the activities of the skeletal muscles. Surface electromyography (sEMG) measures the electrical signal on the skin's surface, which is generated by skeletal muscles. It is often performed while stimulating the relevant motor and peripheral nerves. The measurement may be performed either in an invasive or surface (noninvasive) at the level of a single muscle fiber, single motor unit, or the entire muscle [20]. The processing of information from the EMG enables diagnostics of muscle and neuromuscular disorders, or to analyze or use the sEMG for rehabilitation or robot control [21, 22]. However, for its relative simplicity in acquisition and rich neural information provision content, EMG plays an important role in the control of modern robotic prostheses [23, 24].

The stochastic nature of EMG makes the search for repeatable and reliable characteristics of the signals very challenging [25, 26]. However, it is still used individually in prosthetics research as there are serious studies to develop a system for evaluating pattern recognition algorithms on hannes prostheses [27]. In a related context, sEMG is not sufficiently used as a tool for clinical decision-making, where reliable extraction of information requires knowledge of appropriate methods as an indicator for measuring muscle activity, analysing sEMG and understanding of basic biophysics. However, there are attempts to bridge the gap [28] and consider the challenges between theoretical knowledge and practical application in order to employ it in clinical scenarios in rehabilitation medicine.

fNIRS

One of the neuroimaging technologies on which hopes of creating a control system for prosthetic limbs may be based. The results and classification accuracy recorded by fNIRS when used individually are lower than the results recorded with other technologies when used as a hybrid system, i.e. superior to the hybrid system. Research on fNIRS technology is extensive and ongoing [29, 30], and to this day there are ongoing studies on the use of fNIRS technology for prosthetic control as shown in Figure 4.

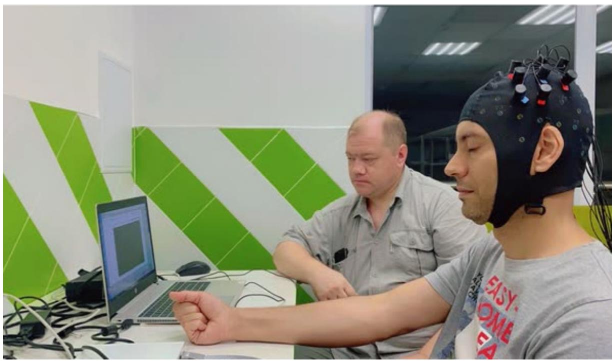

Fig. 4. Shows a subject performing experimental tasks in a laboratory at Belgorod State University in Russia in pursuit of finding a control system for prostheses

Рис. 4. Показан испытуемый, выполняющий экспериментальные задания в лаборатории Белгородского государственного университета в России в поисках системы управления для протезов

Today fNIRS has wide application in various fields such as neurology, clinical application, neonatal application, pediatrics, cognitive and social neurology, neuroprosthetics with robotic control, neurorehabilitation and others. Recent research shows that fNIRS can form a hybrid system with EEG or with EMG.

Hybrid mode

The main essence of the hybrid system configuration of any system, whether it is a plant, animal, technical, or software system, is that one of the systems must complement the shortcomings of the other, noting that the hybrid system configuration must be conditioned to achieve outputs that are not equal to those received from the autonomous system, however the results must be clearly superior when using the hybrid system. On the other hand, when proceeding to the formation of a hybrid system, it should be if there are at least partially similar characteristics in both systems, which allows us to simply form a hybrid system.

EEG+fNIRS

The possibility of configuring a hybrid system of fNIRS and EEG is consistent with the above, because the outcomes that obtained from these techniques are better than those obtained when used independently, and some characteristics of these two techniques are similar. In the composition of EEG, sensors-electrodes are placed on the skin of the upper part of the skull (international system "10-20") and capture electrical signals from neurons in the brain. This can be measured in the electrical activity of the brain, can monitor complex neuronal activity and its changes [14].

EEG has many advantages and disadvantages that may be compatible with fNIRS. For example, they are compatible with non-surgical intervention, EEG technology may be affected by its very high sensitivity to artifacts; therefore, fNIRS may become an alternative to this feature, or there may be a challenge facing the hybrid system involving these two technologies. In addition, the EEG signals provide high temporal resolution, allowing real-time measurement of motor imagery [31], which can be converted into control signals to assist with motor movements. Unlike fNIRS, which suffers from a time delay of 3–5 seconds in detecting areas of brain activity. It has also been widely reported that better BCI performance can be achieved with multimodal analysis instead of standalone EEG signals. Therefore, multimodal studies that assess both the electrical activity of the brain as well as the activity of the circulatory system attracted great attention of researchers [32, 33]. Moreover, recent scientific studies based on the analysis of activated brain regions using fNIRS proved that the auxiliary motor cortex was obviously activated during motor imagery, which means that hybrid signaling with a hybridization strategy can enhance stability and error ignoring in BCI systems, which qualifies it to be a valuable technique for practical applications

sEMG+fNIRS

The sEMG and fNIRS methods can be used separately or together. In scientific studies related to sports activity and neurophysiology, the focus has been on various sports disciplines as subjects of research [34] or the use of fNIRS as a hybrid system use it as a hybrid system with fNIRS to enhance the accuracy of classification of transuterine prostheses [35].

The EMG frequency ranges vary from 0,01 to 10 kHz, depending on the type of examination (EMG or sEMG). The most useful and important frequency ranges are within the range of 50–150 Hz [20]. While the fNIRS frequency is approximately equal to 1 Hz at 830 nm, which is the optimal wavelength [14, 36]. Several scientific studies have focused on the implementation of fNIRS and EMG technologies in motion but were not related to the interrelationship of signals during specific sports in dynamic movements. Moreover, most of them do not include a description of the signal analysis methods. Kimoto et al. found it possible to perform simultaneous EMG, mechanomyography (MMG) and near-infrared spectroscopy (NIRS) measurements at a local position using a wireless multi-layered sensor, which could be used to predict muscular fatigue [37].

Giminiani D. et al. [38] implemented a recently developed integrated quadriceps muscle oximetry/EMG system, when comparing regional muscle oxyhemoglobin saturation and surface EMG data measured under resting and dynamic conditions (treadmill run and strength exercises). When recording oxygen consumption and muscle activity of the gastrocnemius muscle of the left leg for participants, Daniel N. et al. found positive correlations between EMG and fNIRS signals, where the signal correlations between the participants with the most active and least active life style [39]. In a related context, the shapes of the changes in the EMG and fNIRS signals during exercise suggest a mutual relationship during dynamic movements. The close and significant positive correlations between cerebral oxygenation changes (fNIRS) and EMG signals during motor tasks provide evidence for creation hybrid system used to further explore the mapping relationship between brain activity and motor task execution and can be directed toward clinical studies.

It is noteworthy that the composition of the hybrid system is not limited to the work of prosthetics only, but extends to multiple areas for example, the hybrid system consisting of EMG and NIRS is used to monitor muscle fatigue [40]. The superiority and insuperiority of the technologies supporting the creation of a hybrid bionic control system are listed in Table 1.

Table 1. **Superiority and insuperiority of EEG, EMG and fNIRS technologies respectively**

Таблица 1. **Превосходство и непревосходство технологий ЭЭГ, ЭМГ и fNIRS соответственно**

Positives	Minuses
EEG	
➢ Low cost. ➢ Portable, non-invasive and easy to use. ➢ Can provide high temporal resolution of brain activity.	➢ Low spatial resolution due to wide distribution of electrodes on the scalp; ➢ Susceptible to artifacts related to eye movements, muscle contractions, etc., which in some cases may make data interpretation difficult or impossible;
EMG	
➢ Extremely high temporal resolution as well as excellent source localisation capabilities.	❖ Requires expensive equipment to set up and operate. ❖ Requires highly trained personnel for proper calibration and signal processing. ❖ Susceptible to environmental interference, such as electromagnetic fields generated by nearby electronics, which can distort readings if not properly shielded from these sources before taking measurements.
fNIRS	
➢ Portable and low cost compared to other IMC technologies. ➢ Highly sensitive and capable of detecting changes in oxygenated blood levels at different depths of brain tissue with good accuracy when properly calibrated.	➢ Lower temporal resolution than that of EEG or MEG systems, due to their dependence on hemodynamic reactions, rather than on electrical signals directly from neurons. ➢ Not suitable for measuring deep brain structures, since it is based on the transmission of light through the bones of the skull, which may be hindered by thicker skulls or dense bone structures such as those of the elderly or children under the age of 5, respectively.

The experimental results of previous studies of both modes are shown in Table 2.

Table 2. **Comparison of classification accuracy results for qualified systems (independent and hybrid mode)**

Таблица 2. **Сравнение результатов точности классификации для квалифицированных систем (независимый и гибридный режим)**

Reference and year of publication	Independent or hybrid mode	Method	Accuracy or the average value of accuracy
[41], 2021	EEG	Cross-cutting shallow architecture	83.20%
[42], 2022	EEG+fNIRS	Vector-phase analysis	82.%,89,87,86
[43], 2022	EEG	Multiple built-in transfer training.	83.14%
[44], 2022	EEG+fNIRS	fNIRS-guided attention network (FGANet).	78.59% ± 8.86
[45], 2021	fNIRS	NN_LSTM, NN_ConvLST, NN_ResNet	91%
[46], 2023	EEG+fNIRS	FBCSP+PCA+SVM, GLM+MBLL.	92.25.% ± 4.99
[47], 2020	fNIRS	K Nearest Neighbors (KNN)	above 90%
[48], 2017	EMG+fNIRS	SVM, LDA	86.4%
[48], 2017	EMG	SVM,LDA	72.2%
[49], 2021	sEMG+fNIRS	LDA	96.4.% and 94.1.%
[50], 2023	sEMG	CNN-LSTM	70%:30%
[51], 2020	sEMG+fNIRS	LDA	78 - 81 %

It is noted in Table 2, that the accuracy value obtained by different methods, but we point to the evidence of the superiority of the hybrid bionic control system. For example, using SVM, LDA method, the accuracy value obtained for the hybrid system is 86.4%, and in the same method, the accuracy value obtained for the system individually is 72.2%.

Discussion and results

An analysis of the scientific literature has shown that all known and qualified methods for creating a hybrid control system have fundamentally irreparable disadvantages and today have significant limitations in their use for controlling electronic prostheses when used with independent immobilization. In this regard, the most promising in the near future seems to be the use of embedded control systems using neural interfaces based on various physical principles. In these neural interfaces, the disadvantages of one method are compensated by the advantages of another. An example of such a combination is the combination of fNIRS with EEG [44], and fNIRS with EMG [49]. With this combination, the neural interface is provided with a high response speed, with high accuracy of recognition of mental commands.

There are successful examples of using such built-in neural interfaces to control both electronic prostheses [46, 48]. As a result and according to what has been proven and documented by experimental scientific studies that have confirmed that the non-invasive hybrid system is the superior system over its component systems. Qualified methods are characterised by the fact that they are non-invasive, do not pose a risk to the lives of healthy people or patients and can be applied safely that makes them very useful in the field of prosthetics. Unlike invasive neural interfaces, their use poses a risk to people's lives.

Conclusion

Precise control of prostheses is one of the biggest problems that currently exist in scientific fields. It is extremely difficult to measure brain activity and convert it into commands for controlling machines and devices using only thoughts. However, modern technologies such as EEG, EMG and fNIRS techniques have independently penetrated into this field and have achieved some success. Each of these methods has its own characteristics and disadvantages, which led to their insufficient effectiveness for controlling prosthetics. A hybrid bionic control system based on these technologies can be created as a solution to achieve higher efficiency of prosthetic control. In order to determine the task of creating a neural network and train it to evaluate the application of fNIRS in signal recognition, there are several types of neural networks. For example, long short-term memory (LSTM), this is due to the fact that such a model allows you to track the direction of changes in a time series due to the presence of short-term long-term memory, but the essential thing remains to increase the accuracy and adequacy of the neural network model is to collect a larger data set.

It should be noted that future developments in the creation of a hybrid artificial control system may not be limited to fNIRS technique with one of the EEG and EMG techniques. However, it may extend to other techniques without fNIRS, but we are likely that fNIRS is the most appropriate wiht the methods of EEG and EMG. fNIRS has proven relatively successful in the management of prostheses at the same time, fNIRS technology is most convenient in combination with EEG and EMG that is confirmed by several recent studies. In the future, this will serve as an incentive to search for these methods independently of each other or in a hybrid form since they are the closest and most convenient to eliminate the shortcomings of each other, which will lead to the creation of a successful hybrid bionic control system for prostheses or rehabilitation and restoration of lost functions.

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Гибридная бионическая система управления протезами: обзор

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Ноги и руки наиболее подвержены потере, и это связано с тем, что они являются выдающимися внешними органами человеческого тела. В связи с участившимися катастрофами, авариями, войнами и болезнями потеря конечностей становится все более частой, что делает человека ограниченным в свободе и передвижении. Таким образом, поиск альтернатив для улучшения жизни человека чрезвычайно важен. Современные бионические протезы являются лучшей альтернативой ампутированным протезам для выполнения эстетических и функциональных задач. Исходя из этого и анализируя наиболее распространенные и используемые методы протезирования, такие как электроэнцефалография (ЭЭГ), электромиография (ЭМГ) и функциональная спектроскопия ближнего инфракрасного диапазона (fNIRS), зная их преимущества и недостатки, сравнивая их и документируя их результаты с результатами литературы и предыдущих экспериментальных исследований как при индивидуальном, так и при гибридном использовании.

В свете этих данных в данной статье выделяются наиболее распространенные технологии и рассматриваются их преимущества и непреодолимая сила, которые могут быть пригодны для формирования гибридной бионической системы управления протезами или реабилитации и восстановления утраченных функций. Основано на наиболее важных исследованиях, которые касались этих технологий как по отдельности так и в их гибридном виде. Кроме того, эта статья дает обнадеживающие перспективы тем кто интересуется научными исследованиями для изучения, сравнения, идентификации и характеристики превосходных гибридных систем, связанных с системами управления экзоскелетом и, в частности, протезами.

Ключевые слова: гибридная бионическая система управления (гБСУ), гибридные системы интерфейса мозг-компьютер гсИМК, нейроинтерфейсы, электроэнцефалография (ЭЭГ), электромиография (ЭМГ), функциональная ближняя инфракрасная спектроскопия (fNIRS), протезирование.

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