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The possibility of unifying neural interfaces to create an integrated control system for prostheses: a brief review

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Резюме

The purpose of research. *To date, neurointerfaces have not been unified to create combined prosthetic control systems. Based on this, this review is aimed at understanding the possibility of integrating neurointerfaces by clarifying the advantages and disadvantages of neurotechnologies related to prosthetics and the possible creation of a combined prosthesis control system.*

Methods. *Analysis of brain-computer interfaces available in the literature in combination with neuroimaging experiments, especially in a hybrid system. A number of databases of scientific literature were used for the analysis, namely Google Scholar, scopus, etc. Links to the database data on the Internet: https://scholar.google.com/, https://www.mdpi.com/journal/sensors, elibrary.ru, https://www.refseek.com, https://link.springer.com/, https://www.base-search.net*

Results. *Brain-computer interfaces are currently being used in a wide variety of fields, including to improve the lives of people with disabilities. However, individual neural interfaces have certain disadvantages that make it difficult to use them to control mechanical devices, including prosthetic limbs. Hybrid neural interface systems (as an integrated software and hardware complex) are significantly superior to those obtained using separate neural interfaces, and these systems can be used for medical purposes.*

Conclusion. *This review provides a brief overview of the disability of people with missing upper limbs and how to improve their lives with prosthetics. The analysis of various hybrid methods of brain research is given. It can be noted that fNIRS technology is the closest technology that can facilitate the integration of neural interfaces, since it has advantages that make it a tool that complements other technologies, its advantages make up for the inherent disadvantages of fNIRS. It has been established that the hybrid system provides a clear advantage over individual neural interfaces.*

Keywords. *disability; brain–computer-interface; electroencephalography; surface electromyography; integrated control system; prostheses.*

Conflict of interest: *The Authors declare the absence of obvious and potential conflicts of interest related to the publication of this article.*

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Возможность интеграции нейроинтерфейсов для создания комбинированной системы управления протезами: краткий обзор

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Abstract

Цель исследования. *На сегодняшний день нейроинтерфейсы не унифицированы для создания комбинированных систем управления протезами. Исходя из этого данный обзор направлен на представление возможности интеграции нейроинтерфейсов путем выяснения преимуществ и недостатков нейротехнологий, связанных с протезированием, и возможного создания комбинированной системы управления протезами.*
Методы. *Осуществлен анализ имеющихся в литературе исследований интерфейсов «мозг-компьютер» в сочетании с экспериментами по нейровизуализации, особенно в гибридной системе. Для анализа использован ряд баз научной литературы, а именно Google Scholar, Scopus и др. Ссылки на данные базы в сети Интернет: https://scholar.google.com/, https://www.mdpi.com/journal/sensors, elibrary.ru, https://www.refseek.com, https://link.springer.com/, https://www.base-search.net.*
Результаты. *Интерфейсы «мозг – компьютер» в настоящее время используются в самых разных областях, в том числе для улучшения жизни людей с ограниченными возможностями. Однако отдельные нейроинтерфейсы имеют определенные недостатки, затрудняющие их применение для управления механическими устройствами, в том числе протезами конечностей. Системы гибридных нейроинтерфейсов (как интегрированный программно-аппаратный комплекс) значительно превосходят те, которые были получены при использовании отдельных нейроинтерфейсов, и они могут быть применены в медицинских целях.*
Заключение. *В этом обзоре представлен краткий обзор инвалидности людей с отсутствием верхних конечностей и того, как улучшить их жизнь с помощью протезов. Дан анализ различных гибридных методов исследования головного мозга. Можно отметить, что fNIRS является технологией, которая может способствовать интеграции нейроинтерфейсов, поскольку имеет преимущества, которые делают её инструментом, дополняющим другие технологии. Установлено, что гибридная система обеспечивает явное преимущество по сравнению с отдельными нейроинтерфейсами.*

Ключевые слова: *инвалидность; интерфейс «мозг – компьютер»; электроэнцефалография; поверхностная электромиография; интегрированная система управления; протезы.*

Конфликт интересов: *Авторы декларируют отсутствие явных и потенциальных конфликтов интересов, связанных с публикацией настоящей статьи.*

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Introduction

At present time, natural organs are not replaced by artificial organs with the same accuracy, and the loss of a limb in itself is a great loss. Continued accidents, diseases, and other problems leave behind a lot of physical problems in people, with less than one percent of all people with disabilities under the age of five [1]. Physically disabled amputees lose their freedom of movement and may develop mental illnesses, leading to isolation from social contact. The concept of disability cannot be reduced to just a physical loss, but it is a heavy and boring feeling that affects a person throughout his life and constantly grows in physically disabled people, who may be mentally disabled, and this feeling may lead them to suicide.

Loss of the lower and upper limbs is one of the most common disabilities because it is the most prominent and most used external organ in people. More than 3 million people worldwide suffer from the disability of arm amputation [2]. The Disability of the upper extremities can be divided into five main parts, as shown in Figure 1 [3].

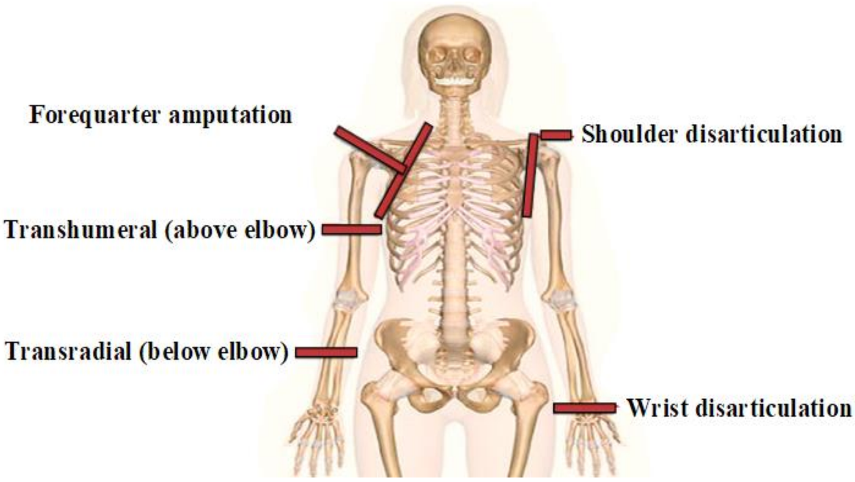

Fig. 1. Upper limb amputation regions with five parts

Deepen the understanding of disability, a multifaceted, multidimensional, complex and interdisciplinary social phenomenon, in all cultures and historical periods, promote greater awareness of the experiences of people with disabilities, advocate for social change that promotes positive emotions without negativity and encourage them to socialize without isolation [4]. The accelerated scientific progress, especially in the technological field, has entered the lives of people with disabilities to find appropriate solutions and ways to improve their lives. The solutions lie in finding artificial substitutes to replace the amputated natural limbs, but they do not come - that is, artificial limbs - with the same precision, feeling, sensation and freedom of movement that their counterpart from natural limbs possesses. The beginning of the idea of prosthetics may date back historically to a large artificial toe made of wood found on the foot of the mummy of an Egyptian woman 3000 years ago and it was the oldest prosthesis in the world and was used then for decoration [5]. If the prosthesis exceeds beyond the idea of aesthetics and contributes to improving the life of a disabled person by performing a motor task, even by 1%, it is definitely better than using it for decorative purposes only.

A prosthesis is a device that replaces a natural limb to beautifully complete the physical structure and perform the tasks and functions performed by the latter. Modern bionic prostheses have actuators that perform the tasks of movements and in order to control these movements, neural interfaces are used- a hardware- software complex for functional interconnection between a biological object (animal or human) and a machine for the direct exchange of information between the human nervous system and the electronic device- to control the drives of such bionic prostheses [6].

The first neural interfaces mentioned in the scientific literature developed by a research group in 1973–1977 [6; 7]. Despite the large number of modern scientific studies and numerous articles, a unified classification of neural interfaces has not yet been developed. The functionality of neural interfaces is based on the real-time detection of patterns of brain activity using neuroimaging methods, such as electroencephalography (EEG), functional near-infrared spectroscopy (fNIRS) and others methods, and on the transformation of the obtained information into control commands for hardware such as bioprosthesis, exoskeleton, neurointerface for attention control, etc. It is known that neuroimaging techniques have advantages and have some inherent disadvantages, and it is reasonable that not all of these techniques share the same disadvantage. In other words, defects that exist in one technique may not be present in the other.

fNIRS in its biggest disadvantages with a depth of no more than 3 cm inside the skull and with time delay of 3-5 seconds in detecting areas of brain activity make it an incomplete method, but it has advantages that make it able to be a tool for receiving or contributing with advantages from and to other technologies to create a technical combination [8; 9].

EEG technology in both its states, invasive and non-invasive, based on direct electrical brain activity has proven its presence in several fields. By using electrodes located on the head surface (non-invasive) is still very low for the exchange of information between the brain and the machine. Despite, it is characterized by very high temporal and spatial accuracy, but in the terminology of using EEG as a control interface in prosthetics, its big drawback is that it is highly sensitive to artifacts and this is not at all suitable for using it individually as a control interface for prosthetics [10]. For several decades, surface electromyography (sEMG) signals- based on the recording of muscle activity- are investigated as an intuitive human-machine interfaceto control prosthetic arms [11; 12]. The absence of muscles, the presence of muscular dystrophy, or the remaining part of the muscle is unable to produce muscle activity, all this make sEMG when used individually out of the calculations of the formation of an integrated control system.

Despite the numerous studies and scientific experiments of EEG and sEMG towards prosthetic applications, these two technologies are absolutely unsuitable for the formation of an integrated control system, even if a combination of these two technologies is formed. As for fNIRS, even if it is proved to be unsuitable for prosthetic applications, it will serve as a complementary tool for unifying neural interfaces to form a promising integrated prosthetic control system.

Materials and methods

The research methodology (as shown in Figure 2) was limited to the most common techniques that are the focus of modern studies within industrial limb applications and through which an integrated control system can be created. Despite the fact that fNIRS is used in various studies and has a wide application in various fields, the research methodology considered relevant research, articles and studies towards prosthetic limb scenarios.. The ultimate purpose of this review is to examine the fit of the fNERS neuroimaging technique with other techniques toward the goal of the review. In addition, this review compared the results of studies involving these techniques in single use and hybrid use. Based on well-known databases, namely Scopus, Google Scholar, and various 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, hundreds of relevant articles were reviewed, many of those that did not go to the essence of the topic were discarded, and those that did not carry modern ideas were deleted, after which followed the recommendations of experienced people and considered their comments in order to strengthen the methodology and targeted analysis.

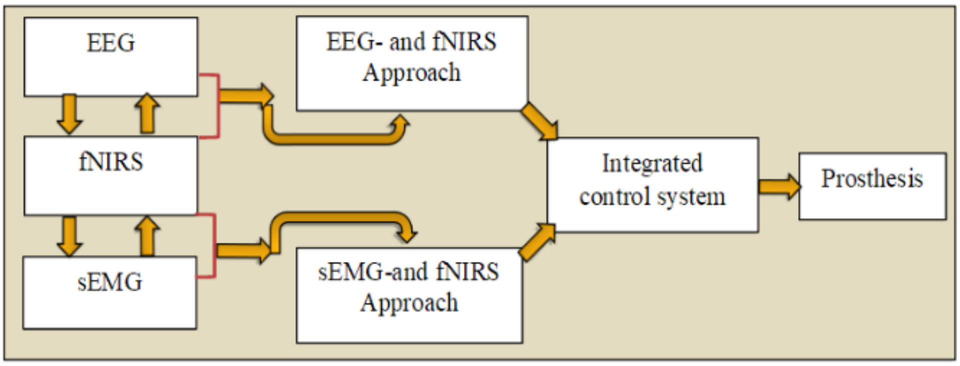

Fig. 2. Research methodology based on an integrated control system for prostheses

Brain-computer-interface (BCI)

BCI or simply a neural interface. is one of the most rapidly progressing topics in various applications of science and technology, including physics, neuroscience, engineering etc. [13], which is closely related to physics and this would require the classification of neural activities in the brain to different states [14]. Historically the first EEG-based BCI enable to generate a control signal for functional electrical stimulation was in 1999 [15]. In 2003 was the combination of BCI and functional electrical stimulation, and thanks to this combination, BCI was developed which can help paralyzed patients, to control their paralyzed limbs, therefore that the patient was able to take a cylindrical object, such as glass with water [16].

BCI is a very promising option for controlling neuroprostheses [14; 17]. Control command based classification, in its active state use changes in brain activity, which are directly and consciously controlled by the operator of the neural interface, regardless of external events, for control commands. The advantages and disadvantages of neuroimaging techniques appear together in one method and this in itself is a challenge. One of the main challenges of BCI systems is the control of prostheses by the electrical activity of the brain, whether using them individually or in a hybrid method [18]. By 59 % of the BCI system uses only one type of physiological signal, mostly from EEG.

There is a hybrid BCI which takes advantages of different techniques [19] and includes active (a complex external device e.g a prostheses- is controlled by a series of functional components of the control system) and passive (for monitoring the brain activity provide important information about operator's mental condition e.g, emotional state- when the command classification algorithm of the active BCI is dynamically adjusted depending on the state of the operator diagnosed by the passive BCI. The most important thing that concerns all researchers in the field of prosthetics is to find artificial systems similar to natural limbs.

The development of active prostheses - with external strength and mobility provided by actuators, offering high performance and functionality, is at the expense of complexity [20]. A growing field and a high goal of scientific research, which is focused on the design of new and powerful control systems and methods of interaction between prostheses and human intention (physical and imaginary implementation) that means the need to unify the neural interfaces to form a promising system in prosthetics.

EEG and fNIRS approach

EEG in both its states is an invasive and non-invasive method used to record brain signals. In its invasive state using implanted electrodes inside the brain such as electrocorticography or intracranial (iEEG) has high spatial and temporal resolution, wide bandwidth, high amplitude and small sensitivity to artifacts [21], allows efficient decoding of small brain signals, in particular those related to motor skills [22]. In exchange for these advantages, its disadvantages do not allow its use, because the implantation of electrodes inside the brain may cause brain infection, as well as the cells adjacent to those electrodes may die, and the connective tissue dies, necessitating the replacement of those electrodes continuously. Experiments of EEG interfaces, successfully conducted on monkeys [23; 24], but for humans, the EEG method of controlling bionic prostheses from both hygienic and ethical aspects is also not used.

The combination of EEG-fNIRS carries a clear signal and is a promising approach because of its low cost, portability flexibility, low interference, and good spatial and temporal resolution [9; 10]. In terms of signal recording, combining EEG and fNIRS provides additional information about the bioelectric activity of the brain. In addition, the combination of fNIRS and EEG has certain unique characteristics, as the rationale behind their combination is their dependence on a physiological phenomenon called neurovascular coupling [25] within the brain, which makes them more useful in certain applications. At present, there are numerous studies active in the study of the combination of these techniques, particularly for prosthetic control purposes. This greatly encourages the creation of a system that may be the most promising for controlling prosthetics [26; 27].

EEG based on non-invasive method has also high temporal and spatial resolution, however, the rate of information transfer between the brain and EEG in its non-invasive state is still very low, in addition, what is remarkable about EEG is its high sensitivity to artifacts. It is clear that the control of prostheses requires high accuracy in advance to transmit information from the brain to the control device and, as such, EEG is also unsuitable for prosthetic applications, if used individually. EEG has not been individually suitable for prosthetic applications, but recent scientific studies have proven its existence as a very suitable hybrid system with the fNIRS technique. For example, the classification accuracy of the EEG, fNIRS based BCI system individually is (85.64 ± 7.4%), (85.55 ± 10.72%) respectively while the hybrid EEG-fNIRS based BCI had to achieve higher classification accuracy (91.02 ± 4.08%) and efficiency by integrating their complementary characteristics [28].

sEMG and fNIRS approach

Electromyography (EMG) is another promising platform for controlling neural prostheses using muscle electrical activity [29] and for neurorehabilitation [30]. Surface electromyography measures the electrical signal generated by the skeletal muscles on the surface of the skin. The absence of muscle or the presence of muscular atrophy renders this technique completely inappropriate forcreating a prosthetic system [31]. Recent studies have demonstrated positive correlations between EMG signals and fNIRS. These correlations may provide evidence that a combination of these two techniques can be used to further explore the mapping relationship between brain activity and motor task execution and could be directed toward clinical studies [32; 33]. Although it is commonly used in modern experimental studies. However, it is impossible to form a unified neural interface system to control prosthetics.

Results and their discussion

Despite the shortcomings inherent in fNIRS technique, scientific research has not stopped its function as a tool for controlling prostheses, and studies are continuing to the present . In a study related to the topic of the article, in the photograph (Figure 3) is a doctor of computer science named Salah from Iraq where he is conducting an experiment to research and develop a control system for prostheses using fNIRS, the results of the experiment will be announced in the near future.

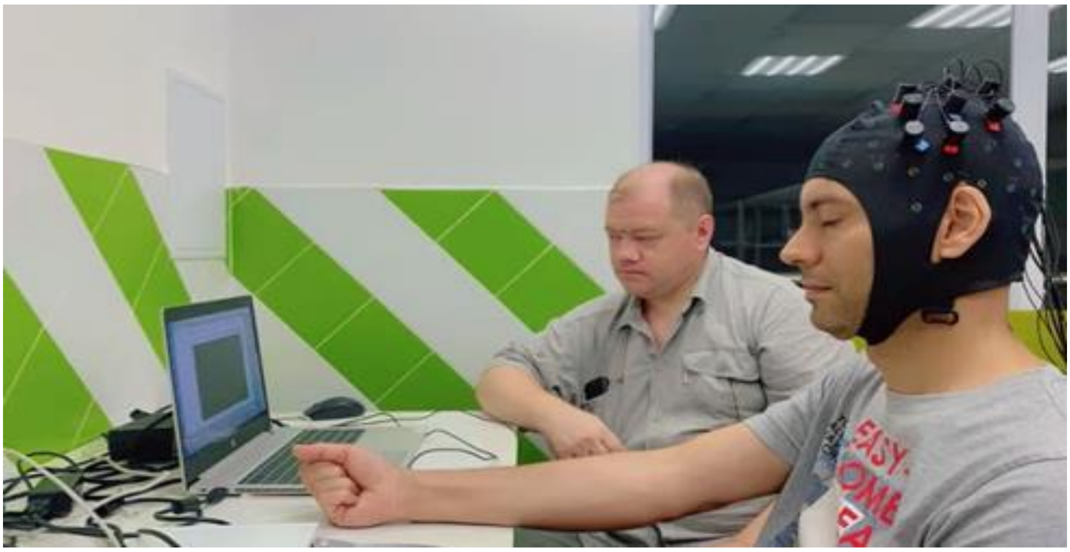

Fig. 3. Shows a photograph of one of the study participants performing experimental tasks in the field of prosthetics in a laboratory of the Belgorod State National Research University

There are recent studies that have even included the challenges facing this method, for example rethinking the delay hemodynamic responses [34]. Even if future studies prove that the fNIRS technology is not suitable for creating an integrated control system for prostheses, it is really suitable for unifying neural interfaces, forming a combination of an integrated system (hardware software), and this is documented by the results of recent experimental studies, for example fNIRS with EEG [35; 36] and fNIRS with EMG [32; 37]. And all this falls on the shoulders of future studies for the purpose of unifying neural interfaces or finding a control system either from the aforementioned techniques, or it may be from other techniques, although the techniques mentioned in the review are commonly used.

Conclusions

Neural interfaces have succeeded in controlling prostheses in their individual cases in some places while failing in others. There are successful examples, and multiple researches prove the great superiority of a combination of neural interfaces for interested studies in electronic prosthetics or rehabilitation applications, for example, the combinations of fNIRS with EEG and fNIRS with sEMG. In brief, summarize the following:

1) fNIRS is still in the circle of study and experimentation, therefore it is not true in the current time to say that it is not suitable for controlling prosthetic limbs.

2) fNIRS and EEG are non-invasive methods can form a hybrid system that may

be a candidate system to be the most promising technology for controlling prosthetic limbs.

3) fNIRS can form a hybrid system with sEMG which may also be a candidate system to be the most promising technology for controlling prosthetics.

4) There are no scientific studies indicatingany superiority between 2 and 3.

5) 1, 2 and 3 will remain important for future studies and research for the purpose of unifying neural interfaces in order to create an integrated control system for prostheses.

References

1. Ronald J.B., Loren E.W. Introducing Disability Studies. 2nd ed. Lynne Rienner Publishers; 2021. 289 p.

2. Sachin K., Dhruv G., et al. A novel deep learning approach to predict subject arm movements from EEG-based signals. *Neural Computing and Applications*. 2023;(35):11669–11679.

3. Neelum Y.S., Zareena K., et al. fNIRS-Based Upper Limb Motion Intention Recognition Using an Artificial Neural Network for Transhumeral Amputee. *Sensors*. 2022;22(3):726. https://doi.org/10.3390/s22030726

4. Philip M. Ferguson Disability Studies: What Is It and What Difference Does It Make? *Research & Practice for Persons with Severe Disabilities*. 2012;37(2):70-80.

5. Nerlich A.G., Zink A., Szeimies U., Hagedorn H.G. Ancient Egyptian prosthesis of the big toe. *Lancet*. 2000;(356):2176–2179.

6. Vidal J.J. Toward direct brain-computer communication. *Annu Rev. Biophys. Bioeng*. 1973;2(1):157–180. https://doi.org/10.1146/annurev.bb.02.060173.001105

7. Ma T., et al. The hybrid BCI system for movement control by combining motor imagery and moving onset visual evoked potential. *J. Neural. Eng*. 2017;14(2):26015. https://doi.org/10.1088/1741-2552/aa5d5f

8. Hasan M.A.H., Khan U., Misra D. A Computationally Efficient Method for Hybrid EEG-fNIRS BCI Based on the Pearson Correlation. *BioMed Research International*. 2020;(3):1–13. https://doi.org/10.1155/2020/1838140,

9. Abdalmalak A., Lawrence S. Detecting Command- Driven Brain Activity in Patients with Detecting Command-Driven Brain Activity in Patients with Disorders of Consciousness Using TR-fNIRS Disorders of Consciousness Using TR-fNIRS. Available at: https://ir.lib.uwo.ca/etdhttps://ir.lib.uwo.ca/etd/7055 2020 (accessed 17.03.2024).

10. Hramov A.E., Maksimenko V.A., Pisarchik A.N. Physical principles of brain–computer interfaces and their applications for rehabilitation, robotics and control of human brain states. *Physics Reports.* 2021;(918):1–133. https://doi.org/10.1016/j.physrep.2021.03.002

11. Shahzad W., Ayaz Y., Khan M., Naseer J.N., Khan M. Enhanced performance for multi-forearm movement decoding using hybrid IMUSEMG interface. *Frontiers Neurorobot*. 2019;(13):43.

12. Phinyomark A., Khushaba R.N., Scheme E. Feature extraction and selection for myoelectric control based on wearable EMG sensors. *Sensor*. 2018;18(5):1615.

13. He B., Yuan H., Meng J., Gao S. Brain-computer interfaces. In: Neural Engineering. Singapore: Springer; 2020. P. 131–183.

14. Alejandro A., Carlos A., et al. Biosignal Processing and Classification Using Computational Learning and Intelligence Principles, Algorithms, and Applications. London: Academic Press; 2021. 536 p. https://doi.org/10.1007/978-3-642-008745-7

15. Lauer R.T., Peckham P.H., Kilgore K.L. EEG-Based control of a hand grasp neuroprosthesis. *Neuroreport*. 1999;10(8):1767–1771.

16. Pfurtscheller G., Muller G.R., et al. Thought-control of functional electrical stimulation to restore hand grasp.in a patient with tetraplegia. *Neuroscience Letters*. 2003. 351(1):33–36. https://doi.org/ 10.1016/S0304-3940(03)00947-9

17. Gutierrez-Martinez J. Neuroprostheses: Significance in gait rehabilitation. In: Advanced Technologies for the Rehabilitation of Gait and BalanceDisorders. Singapore: Springer; 2018. P. 427–446.

18. Bhattacharyya S., Mukul M.K. Reactive frequency band based movement imagery classification. *J. Ambient. Intell. Hum. Comput*. 2018;(9):1–14.

19. Nam C.S., Nijholt A., Lotte F. Brain-computer interfaces handbook: technological and theoretical advances. Oxford, UK: CRC Press; 2018. 814 p.

20. Windrich M., Grimmer M., Christ O., Rinderknecht S., Beckerle P. Active lower limb prosthetics: A systematic review of design issues and solutions. *BioMed. Eng. OnLine.* 2016;15(283):140. https://doi.org/10.1186/s12938-016-0284-9

21. Schwartz A.B., Cui X.T., Weber D.J., Moran D.W. Brain-controlled interfaces: Movement restoration with neural prosthetics. *Neuron*. 2006;(52):205–220. https://doi.org/ 10.1016/j.neuron.2006.09.019

22. Lal N., Hinterberger T., et al. Methods towards invasive human brain computer interfaces. In: Advances in Neural Information Processing Systems. Cambridge: MIT Press; 2005. P. 737–744.

23. Velliste M., Perel S., Spalding M.C., et al. Cortical control of a prosthetic arm for self-feeding. *Nature*. 2008;453(7198):1098–1101.

24. Hochberg L.R., Donoghue J.P. Sensors for braincomputer interfaces. *IEEE Eng. Med. Biol. Mag*. 2006;25(5):32–38.

25. Jianeng L., Jiewei L., et al. An EEG-fNIRS neurovascular coupling analysis method to investigate cognitive-motor interference. *Computers in Biology and Medicine*. 2023;(160):106968.

26. Li R., et al. Concurrent fNIRS and EEG for Brain Function Investigation: A Systematic, Methodology-Focused Review. *Sensors*. 2022:22(15):5865. https://doi.org/10.3390/s22155865

27. Ergün E., Aydemir Ö., Korkmaz O.E. A Novel Scrolling Text Reading Paradigm for Improving the Performance of Multiclass and Hybrid Brain Computer Interface Systems. Available at: https://ssrn.com/abstract=4740312 (accessed 12.03.2024).

28. Rihui L., et al. Enhancing Performance of a Hybrid EEG-fNIRS System Using Channel Selection and Early Temporal Features. *Front. Hum. Neurosci*. 2017;(11):1–11. https://doi.org/10.3389/fnhum.2017.00462

29. Tao S., Zhe Y. et al. Review of sEMG for Robot Control: Techniques and Applicationsby. *Applied Sciences*. 2023;13(17):9546.

30. Khorasani A. Hulsizer J. Myoelectric interface for neurorehabilitation conditioning to reduce abnormal leg co activation after stroke: a pilot study. *Journal of NeuroEngineering and Rehabilitation*. 2024;(1):115. https://doi.org/10.21203/rs.3.rs-3398815/v1

31. Martinek R., et al. Advanced bioelectrical signal processing methods: Past, present, and future approach – part III: Other biosignals. *Sensors*. 2021;21(18):6064. https://doi.org/10.3390/s21186064

32. Daniel N., Sybilski K., Kaczmarek W., Siemiaszko D., Małachowski J. Relationship between EMG and fNIRS during Dynamic Movements. *Sensors*. 2023;23(11):1–14.

33. Giminiani R.D., et al. Validation of fabric-based thigh-wearable EMG sensors and oximetry for monitoring quadricep activity during strength and endurance exercises. *Sensors*. 2020; 20(17):1–13. https://doi.org/10.3390/s20174664

34. Wang Z., Fang J., Zhang J. Rethinking Delayed Hemodynamic Responses for fNIRS Classification. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*. 2023;(31):99.

35. Neelum Y.S., Zareena K., Syed A.U., Noman N., Umer F., Ahmed A., Syed Z.H., Umar S.K., Haroon K., Peyman M. Enhancing Classification Accuracy of Transhumeral Prosthesis: Hybrid sEMG and fNIRS Approach. *Digital Object Identifier*. 2021;(9):1.

36. Ali M. U., et al. An Optimization-Based Hybrid EEG and fNIRS – Brain Computer Interface. *Bioengineering*. 2023;10:608. https://doi.org/10.3390/bioengineering10050608

37. Wang Z., et al. Incorporating EEG and fNIRS Patterns to Evaluate Cortical Excitability and MI-BCI Performance During Motor Training. *IEEE Trans. Neural. Syst. and Rehabil. Eng*. 2023;(31):2872–2882. https://doi.org/10.1109/TNSRE.2023.3281855

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