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EVALUATION OF MACHINE LEARNING AND DEEP LEARNING TECHNIQUES APPLIED IN SCI INJURY: A SYSTEMATIC REVIEW

AVALIAÇÃO DE TÉCNICAS DE MACHINE LEARNING E DEEP LEARNING APLICADAS A LESÕES DA MEDULA ESPINHAL: UMA REVISÃO SISTEMÁTICA

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ABSTRACT

The application of technologies associated with the Fourth Industrial Revolution, particularly Machine Learning (ML) and Deep Learning (DL), has expanded into multiple fields of knowledge, promoting greater efficiency in addressing complex professional challenges. In the medical and physiotherapeutic domains, one of the most significant difficulties lies in the effective treatment of Spinal Cord Injury (SCI). In this context, the integration of Artificial Intelligence (AI) techniques into support systems emerges as a promising strategy to enhance therapeutic outcomes, while simultaneously addressing issues related to information security. This study presents a systematic review, following the PRISMA-P methodology, to identify and analyze AI-based techniques applied to SCI treatment. A total of 168 studies were initially identified, and after applying the eligibility criteria, 12 articles (7.14%) were selected for detailed analysis. The findings reveal a variety of therapeutic approaches involving Brain-Machine Interfaces (BMIs), which face challenges related to the heterogeneity of computational systems, sensors, and actuators used in healthcare applications.

Keywords: Artificial Intelligence; Deep Learning; Machine Learning; Spinal Cord Injury;

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RESUMO

A aplicação de tecnologias associadas à Quarta Revolução Industrial, especialmente o Aprendizado de Máquina (AM) e o Aprendizado Profundo (AP), tem se expandido para diversos campos do conhecimento, promovendo maior eficiência na superação de desafios complexos. Nos domínios médico e fisioterapêutico, um dos principais obstáculos é o tratamento eficaz da Lesão da Medula Espinhal (LME). Nesse contexto, a incorporação de técnicas de Inteligência Artificial (IA) em sistemas de apoio desponta como uma estratégia promissora para potencializar os resultados terapêuticos, ao mesmo tempo em que se consideram aspectos relacionados à segurança da informação. Este estudo apresenta uma revisão sistemática, baseada na metodologia PRISMA-P, com o objetivo de identificar e analisar técnicas baseadas em IA aplicadas ao tratamento da LME. Foram inicialmente identificados 168 estudos, dos quais, após a aplicação dos critérios de elegibilidade, 12 (7,14%) foram selecionados para análise aprofundada. Os resultados apontam diferentes abordagens terapêuticas com o uso de Interfaces Cérebro-Máquina (ICMs), que enfrentam desafios relacionados à heterogeneidade dos sistemas computacionais, sensores e atuadores utilizados nas aplicações em saúde.

Keywords: Aprendizado Profundo; Aprendizado de Máquina; Inteligência Artificial; Lesão da Medula Espinhal;

1 INTRODUCTION

Implementing therapeutic alternatives in the healthcare field has always been one of the greatest challenges of technological development, either due to the complexity of the human body or ethical challenges. The World Health Organization (WHO) defines Spinal Cord Injury (SCI) as a disease that affects the multidisciplinary aspects of the patient's life and everyone around them, affecting domains of physical and mental functions (Ehrmann et al., 2020). With over 10,000 accidents per year in the US alone, the most frequent consequence of SCIs is the loss of muscle mass due to inactivity, which is exacerbated by aging through sarcopenia (Pisotta et al., 2015).

Fortuitously, key enablers of alternative therapies in the physiotherapeutic and medical fields arise with the application of fourth industrial revolution technologies, specifically with the use of Artificial Intelligence (AI) for manipulation of Brain-Machine Interface (BMI) (Lai et al., 2021). The 4th Industrial Revolution, or as it is popularly called - Industry 4.0, is the revolution of cyber connected systems allowing devices to exchange information. It is based on integrating information and communication technologies, allowing the generation of new strategies and business models (Piana et al., 2022). AI is one of the domains of mathematics that has the potential to improve healthcare techniques, expanding human capacity in cooperation with the computer using innovative decision-making techniques for the patient's clinical case (Kahile et al., 2021), being able to extract relevant information and predict conditions to solve specific and generic cases (Dillen et al., 2022).

Traditionally, from electromyography readings, healthcare professionals collect information of myoelectric sensors of the patient during therapy (Popovic et al., 2000). Nowadays, through the use of cyber systems, it is possible to cross different elements of software, hardware, sensors, and actuators, which can collaborate through Internet of Things (IoT) networks and interact through AI (Rompaey et al., 2022), providing inspiration for improving clinical treatments (Lai et al., 2021). However, the current state of the art requires that the technology be evaluated and ensured also through the perspective of regulatory policies and legislation, since sensitive patient data may be granted to unauthorized individuals (Rompaey et al., 2022).

This article highlights an analysis of research on the use of AI and Machine Learning (ML) Systems for the physiotherapeutic treatment of Spinal Cord Injury, observing their benefits, drawbacks, impacts and implications, considering legal and ethical principles.

2 THEORETICAL BACKGROUND

2.1 Spinal Cord Injury

According to Lilley et al. (2020), spinal cord injuries result in loss of sensory and motor function and cause other problems such as sexual dysfunction, bladder and bowel dysfunction, infections, chronic pain, and cardiac and respiratory problems. The author reports that treatment options in humans are limited, focusing on adaptive therapies and rehabilitation, and managing secondary complications. SCI is the result from traumatic events is a multifactorial process that causes local cellular damage followed by secondary reactive processes, including ischemia, inflammation, edema, cell death, axonal degeneration, gliosis, and scar tissue formation. It is commonly attributed to a failure in the regeneration of nerve fibers derived from the brain through the injury (Lai et al., 2021).

2.1.1 Rehabilitation Treatments for SCI

The study by Pisotta et al. (2015) presents the following treatments for sensorimotor disorders, however, they do not apply to severe cases such as amputation or spinal cord injury:

1. Surgical techniques to reduce functional deficits and promote movement independence, but due to their invasive nature, they become less transferable to daily life conditions compared to other solutions.
2. Pharmaceutical treatment, used to intervene in pain and clonus, usually brings relief of symptoms, but with controversial long-term efficacy.

3. Physiotherapeutic treatment, focused on avoiding muscular hypotrophy through sessions of passive movements. This type of treatment presents general benefits, but is affected by limitations related to task specificity, complexity, time consumption, and dependence on specialization. Another problem is the difficulty of accurately measuring sensory-motor improvements to balance with the amount of assistance provided due to the patient's continuous evolution.

In recent years, technological development has brought advances in automated rehabilitation, with a specific focus on repeatability and quantification, where robot-assisted training has resulted in more precise and long-lasting recovery of sensory-motor functions in patients. The use of robots in treatment allows for monitoring and evaluation of progress in rehabilitation, which in more severe cases such as SCI, significant advances have been made in treatment through the interaction between cognitive neuroscience and biomedical engineering, such as brain-machine interfaces.

Despite the variety of devices and technologies used in therapies, these equipments have in common that the biological signals carrying neural information are captured by sensors, which translate brain signals using decoding algorithms. The connection to the nervous system can occur in two ways: invasive or non-invasive, as described in the Biomedical Engineering section below.

2.2 Artificial Intelligence

AI combines general-purpose technologies that can be applied across all fields of human knowledge, encompassing various types of industries and activities simultaneously (Rompaey et al., 2022), in order to apply computational, mathematical, mechanical, logical, and even biological techniques to understand, associate, and describe, so as to process vast data sets using algorithms in support of human cognitive processes (Kahile et al., 2020).

One of the branches of AI and one of the most applied methods is Deep Learning (DL), which has proven to be a good alternative for performing decoding actions of biosignal control systems, enabling the construction of an ML model, with the acquisition of complex values in hyperparameters, facilitating subsequent data processing processes for predicting values in trained models (Dillen et al., 2022).

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Figure 1 – Flowchart for decoding user commands for biosignal processing and actions through AI for biosignal processing and action

Source: Dillen et al. (2022).

Through a convenient and non-invasive format, data can be efficiently acquired from an electromyography system, processed, and then classified according to the criteria established in the machine (Wang et al., 2018), potentially reducing the clinical suffering influence of many therapies to predict endpoints in complex cellular mechanisms involving SCI (Lilley et al., 2020). With this approach, electrical impulses produced by tissues can be mapped and reproduced by artificial generators of electrical impulses, recreating the stimulation of myocytes (muscles) (Lai et al., 2021).

Figure 2 – Proposal of a neuronal mapping microelectrode model serving as input data for a machine that, through AI, replicates electrical impulses in muscle tissue

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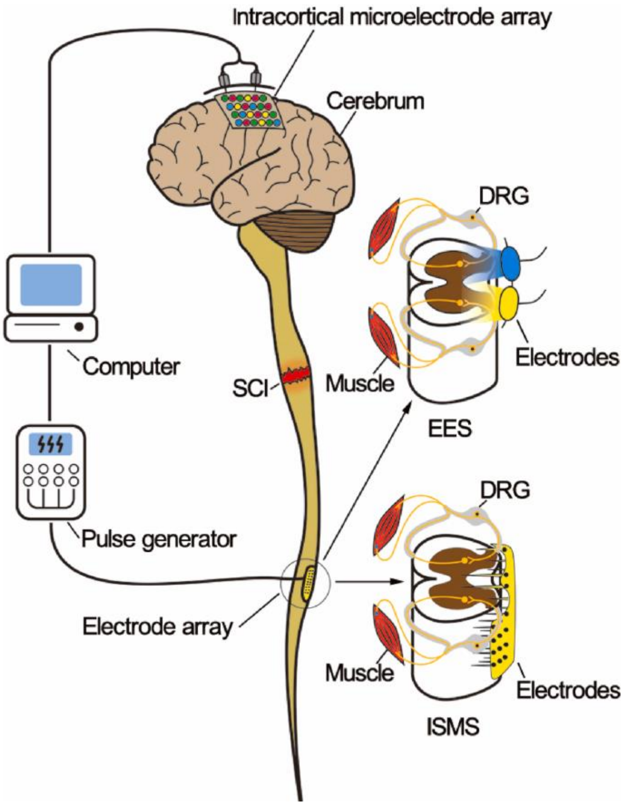

Source: Lai et al. (2021).

2.3 Biomedical Engineering

Several clinical conditions dramatically affect the constant exchange of stimulus between the body and the brain, but advances in biomedical engineering have been providing promising solutions to overcome this communication failure. Technological developments have been able to transform neuronal electrical activity into computational input for robotic devices, giving rise to brain-machine interfaces. The combination of rehabilitation robotics and experimental neuroscience has allowed the emergence of clinical protocols that provide technological solutions to circumvent neural disconnection and restore sensorimotor functions. The greatest challenge for the use of these technologies is the translation of signals from brain-machine interfaces into sensory feedback and the incorporation of these interfaces into daily activities (Pisotta et al., 2015).

In the study by Pisotta et al. (2015), the authors state that the integration of the robotic device and the human brain can occur invasively, where electrodes are connected to the living brain. In this

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case, neural activity is recorded and translated in real-time into computational commands to control the robotic device. However, its implementation in clinical procedures is still very limited due to the limited availability of devices. Similarly, Bi-Quin et al. (2021) report that the limitation of this technology is the scarce number of usable channels in most commercially available devices, high risks of infection or rejection for invasive devices, anatomofunctional neural plasticity and cell death.

Another way of integration with robotic devices is non-invasive, where neural activity is captured by electroencephalography (EEG), with electrodes positioned on the scalp. Compared to the invasive method, the non-invasive has a lower signal quality, requiring the system to have strategies from other levels of abstraction that can eliminate signal noise. In addition to EEG, electromyography (EMG) can be used when peripheral neural signals are still available through residual muscle activity coding. The interfaces that combine EEG and EMG to create a hybrid system are the most recent advance in neuroprosthetics and the most promising future direction of brain-machine interface research (Popovic et al., 2000) (Wang et al., 2018).

3 METHODOLOGY

This study is based on a systematic literature review guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses Protocol (PRISMA-P)[1] methodology.

Initially, a comprehensive search strategy was developed and applied to eight widely recognized scientific databases in the fields of health, medicine, engineering, and technology: ScienceDirect®, ACM Digital Library®, IEEE®, SciELO BR®, Web of Science®, PubMed®, Cochrane®, and Rayyan® (used as a collaborative screening tool). These databases were selected due to their relevance and frequency of use in similar studies (Table 2).

The first stage consisted of applying the search string[2] adapted to the syntax of each database, on November 20, 2022. This search retrieved 164 references (Figure 3), without any restriction regarding publication language, date, or format.

Table 2 – Databases used for the research

[1] Available in: https://doi.org/10.1136/bmj.i4086, access in December/2024.
[2] (“Artificial Intelligence” OR “Machine Learning”) AND (“SCI” OR “Mioelectric”) AND ("physiotherapy") AND ("System")

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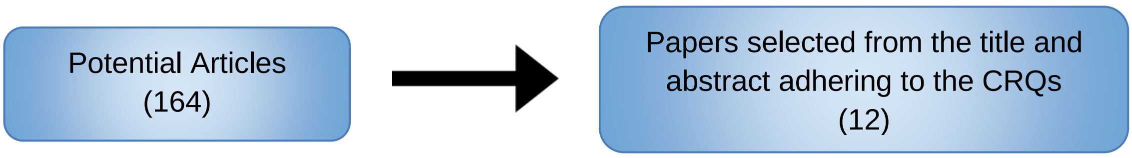
Database	Link	Results
Science Direct	https://www.sciencedirect.com/	75
ACM Digital Library®	https://dl.acm.org/	5
IEEE®	https://ieeexplore.ieee.org/	0
SCIELO BR®	http://www.scielo.org/	0
Web of Science®	https://www.webofscience.com/	84
PUBMED®	https://pubmed.ncbi.nlm.nih.gov/	0
COCHRANE®	https://www.cochranelibrary.com/en/	0

Source: The authors (2024).

Figure 3 – Work selection process



Source: The authors (2024).

In the second stage, titles and abstracts were screened independently by both reviewers using Rayyan®, and the inclusion criteria were applied based on the study's objectives and research questions (CRQs). This screening process was conducted in blind mode to avoid bias. After applying the criteria, 12 articles (7.3%) were considered eligible for full-text analysis.

In the third stage, the full texts of the selected studies were analyzed in detail. The information extracted was cross-validated by a third reviewer to ensure reliability and consistency of data interpretation.

To support the review, three complementary research questions (CRQs) were formulated (Table 2):

Table 2 – Relationship of research questions and main motivations regarding the study objectives

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ID	Research Question	Main motivation
CRQ01	What research has been published addressing the topics of AI for SCI treatment?	Identify which studies focus on the therapeutic use of AI technologies and what technological advances have been promoted.
CRQ02	What are the impacts of these studies on research and field practice for treating SCI patients?	Evaluate in which situations therapies are favorable, as well as their perceived benefits and drawbacks by specialists.
CRQ03	Do the studies consider ethics and regulation in handling patient data?	Identify if studies have ethical evaluation prerogatives regarding the use of patient information with the technological use of AI, if they are following legal regulations and requirements, also evaluate the privacy of sensitive data.

Source: The authors (2024).

The extracted data were then synthesized and categorized based on thematic relevance, technological application, therapeutic results, and ethical implications, as detailed in the following sections.

4 PRESENTATION OF RESULTS

4.1 Data Extraction Strategy and General Aspects

This section reports the aggregated results by research question based on the data extracted from the primary studies.

Due to the data including qualitative responses, diverse approaches were observed for synthesizing the information, applying descriptive synthesis to facilitate mapping and visualization of findings using graphs, tables, and charts.

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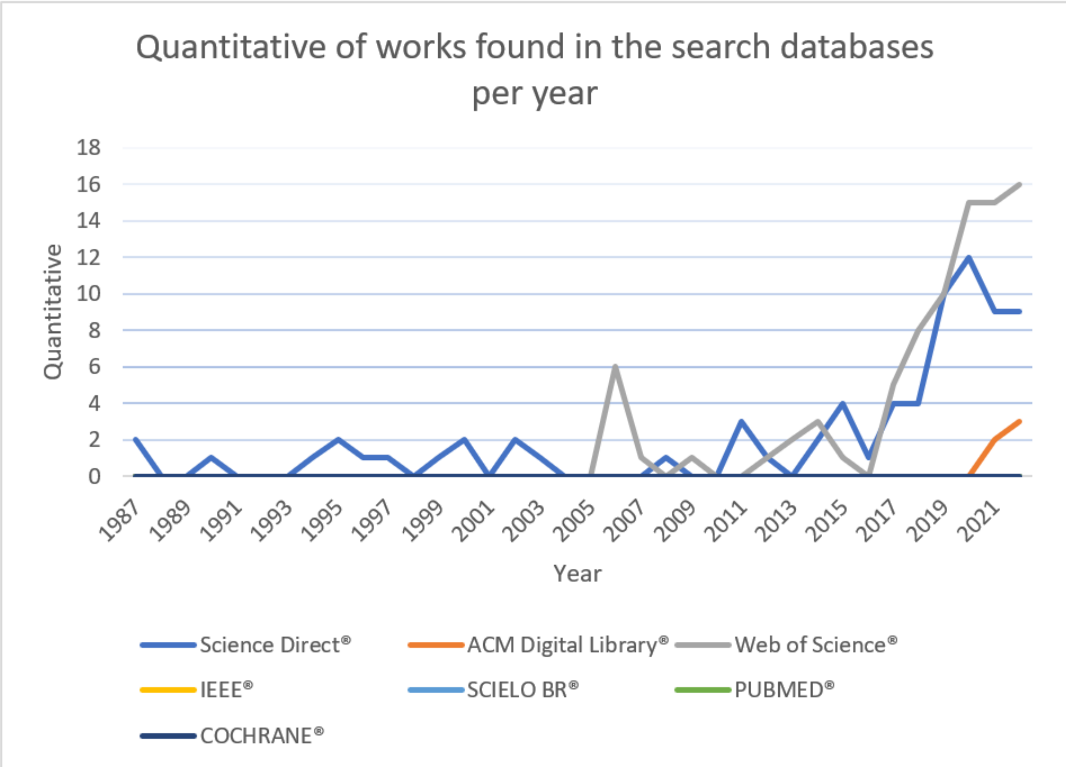
From a quantitative perspective providing an overview of the articles initially found in this study, Figure 4 presents the relationship between the number of articles found in the databases by year; the extraction window obtained results from 1987 to 2021. The different line colors, according to the legend, indicate the databases to which they refer.

Figure 4 – Quantitative of works found in the search databases Science Direct®, ACM Digital Library®, IEEE®, SCIELO BR®, Web of Science®, PUBMED®, and COCHRANE®



Source: The authors (2024).

Figure 4 shows a sharp increase in the production of works from 2017 onwards. This may have happened because several AI and ML technologies began to use AI frameworks, which can raise the level of abstraction of the techniques, allowing researchers to focus their efforts on therapies and less on ML algorithms. It is possible to observe that the highest number of studies were located in the Web of Science® database, followed by Science Direct® and then ACM®. No results were found in the others. The location where the study was conducted is a key factor, as it allows mapping the countries that have been dedicated to research in this field. Figure 5 identifies the countries that address the research recovered after the analysis in relation to the CRQs.

Figure 5 – Location of the selected studies

Source: The authors (2024).

As shown in Figure 5, the countries Belgium, Denmark, Italy, Singapore, United Kingdom, USA, Switzerland, China, and India, all located in the northern hemisphere, held the concentration of publications, totaling 100% of the references selected after the filter.

5 DATA ANALYSIS AND INTEGRATION

This section presents the main characteristics of the selected studies, according to Complementary Research Question 01 (CRQ01), Complementary Research Question 02 (CRQ02) and an observation assessment of Complementary Research Question 03 (CRQ03).

5.1 Categorization and Synthesis of Works

For data analysis, all articles were first read in their entirety, followed by a descriptive synthesis of each work in order to obtain their main contributions. The understanding gained from the synthesis of information enabled data categorization according to the approaches proposed by the authors and the creation of a synthesis matrix based on the keywords used in the search sentence, as can be seen in Tables 3, 4, 5, and 6.

Table 3 – List of results filtered by author, year of publication and title of work

ID	Author	Title
1	Dillen, Arnau et al., 2022	Deep learning for biosignal control: insights from basic to real-time methods with recommendations
2	Van Rompaey, Léonard; Jønsson, Robert; Elmose Jørgensen, Kathrine, 2022	Designing lawful machine behavior: Roboticists' legal concerns
3	Kahile, Milind et al., 2021	AI and ML in Clinical Practice and Physiotherapy
4	Robinson, Neethu; Mane, Ravikiran; Chouhan, Tushar; Guan, Cuntai, 2021	Emerging trends in Brain-Computer Interface (BCI)-robotics for motor control and rehabilitation
5	Lai, Bi-Qin et al., 2021	Stem cell-derived neuronal relay strategies and functional electrical stimulation for treatment of spinal cord injury
6	Ehrmann, Cristina et al., 2020	Describing Functioning in People Living With Spinal Cord Injury Across 22 Countries: A Graphical Modeling Approach
7	Lilley, Elliot et al., 2020	Refining rodent models of spinal cord injury
8	Wang, Nana et al., 2018	A Convenient Non-harm Cervical Spondylosis Intelligent Identity method based on ML
9	Pisotta, Iolanda; Perruchoud, David; Ionta, Silvio, 2015	Hand-in-hand advances in biomedical engineering and sensorimotor restoration
10	Walsh, Pauline; Dunne, Lucy E.; Caulfield, Brian; Smyth, Barry, 2006	Marker-based monitoring of seated spinal posture using a calibrated single-variable threshold model
11	Jezernik, Sašo, 2003	Robotic Orthosis Lokomat: A Rehabilitation and Research Tool
12	Popovic, Dejan; Sinkjær, Thomas, 2000	Improved Control for Functional Electrical Stimulation to Restore Walking

Source: The authors (2024).

Table 4 – Synthesis of technology use with a focus on AI

ID	AI Technology
1	The focus of this work suggests different methods and challenges for the cybernetic interaction of interfaces between computer and biosignal acquisition. A systematic evaluation in PRISMA-P format is promoted, considering inclusion criteria for studies that use DL models, as well as the requirement that these have been validated under practical conditions of real-world applications. The authors propose a DL pipeline where the neurological signal is acquired through digital reading, and then subjected to pre-processing, which leads to two possible paths for controller movement, namely 1. Classification (submitted to a high-level controller) or 2.

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	Regression (directly mapped to the device state). In this sense, they emphasize that the integration of systems is the greatest challenge in designing these solutions.
2	This article addresses the challenges facing the legal question, raising concerns about machine behavior and software artifacts. The authors consider an analysis of the etymology used in compliance and legislation necessary, characterizing it as vulnerability in the regulation challenges of AI and Robotics. It is also suggested that in terms of production processes, engineering prioritizes technological functionalities over safety.
3	This work highlights that systems generate an incredible volume of data that cannot be processed or investigated, indicating that AI technologies are fundamental to increasing the cognitive abilities of physiotherapy professionals in benefit of a better analysis for decision making.
4	The study addresses the use of Deep Neural Networks (DNNs) to support Brain-Computer Interfaces (BCIs), Exoskeletons, and Prosthetic Arms. Wearable devices are combined with invasive and non-invasive methods for acquiring brain data and ML for clinical evaluation.
5	This study reports the use of peridural electrical stimulation (EES), capable of modulating the propriospinal neural network. These brain-spine interfaces have the potential to serve as an "AI". Another approach is intraspinal microstimulation (ISMS), which differs from EES because it provides the electrical signal through microelectrodes implanted in the spinal cord. Its use is rare in humans, but experiments with animals report potential benefits of this approach.
6	LASSO (Least Average Shrinkage and Selection Operator) is one of several ML approaches highlighted in the study to identify conditional dependence between two variables with binary data. It has shown to provide stable results in identifying associations between random variables. The data was analyzed using the R software. In items with missing responses, the Random Forest technique was adopted.
7	In this study, an *in-silico*[3] model is defined that can be associated with ML approaches to better predict human experimental outcomes, thereby reducing the use and suffering of animals. The authors also highlight the importance of a worldwide SCI research database to use Big Data techniques and better understand the underlying mechanisms of recovery across species, increasing the potential for successful clinical translation. They suggest that the results would allow for the standardization of preclinical model selection and implementation.
8	Within this work, the approach of AI technology is made through the EasiAI model, which is suggested as a data processing model in three layers: 1. Feature extraction; 2. Feature selection; and 3. Classification algorithm. The feature extraction algorithm is applied with the objective of obtaining the reading of the user's digital signals. The feature selection algorithm called EasiRF uses Random Forest to select the most relevant features. The classification algorithm is based on gradient-boosted regression trees to identify CS (Carpal Tunnel Syndrome) and produce reports for users. These algorithms are lightweight and can be integrated into the user's device to generate reports quickly and without compromising privacy. The authors also suggest performance evaluation metrics for the model, such as accuracy, sensitivity, specificity, False Negative Rate (FNR), False Positive Rate (FPR), and Area Under the Curve (AUC) (the area under the sensitivity and specificity curve).
9	According to the authors, the invasive method offers a superior signal quality compared to the non-invasive method in capturing neural activities. However, they report that it is possible to improve the signal collected by the non-invasive method by using adaptive algorithms during training. One way to implement sensory feedback in future Brain-Machine Interfaces (BMI) is to combine new algorithms capable of converting neural activity into specific motor commands

[3] The term *"in-silico"* refers to computational models that investigate pharmacological hypotheses using tools such as databases, data analysis and mining software, homology models, machine learning, pharmacophores, quantitative structure-activity relationships, and network analysis tools, among others.

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	and make the devices capable of reflecting the complex interaction between different mechanoreceptors.
10	The researchers used a decision tree ML algorithm called J48 to classify data collected from postural flexion vectors with the main goal of identifying the simplest and most accurate way of measuring users' posture. As a result, the overall flexion vector was identified as the best posture indicator, capable of providing 100% accuracy in cross-validation for all tested subjects. After the threshold was identified, the ML model was no longer needed in the proposed work and a visual analysis method was used to evaluate the collected data.
11	The work addresses the development of an Artificial Neural Network (ANN) model to simulate the spinal locomotor circuit, based on programming the model with a central pattern generator. To do this, the researchers included elements in favor of coordinating hip joint oscillators with support from motor interneurons. The model was evaluated in conjunction with the Lokomat, which is a highly advanced exoskeleton widely available in the global medical and physiotherapy field that can attach to a patient immobilized by nervous system damage to support the walking process. The Lokomat functioned as a controller for obtaining force and position sensor information. The Artificial Neural Network (ANN) interface was also applied using Simulink, which is software developed by MathWorks, as a tool for graphical modeling and simulation and analysis of dynamic systems in conjunction with MATLAB to support the spinal neural model.
12	The paper does not specify in terms of language or technology, providing only insights into how important it becomes to analyze patient data for the production of artificial reflex systems to improve biomechanical therapies and individualized patient life, evaluating circumstances of hybrid controllers that rely on rules under sensors and actuators for functional electrical stimulation.

Source: The authors (2024).

Table 5 – Synthetic matrix for evaluating therapy results for SCI

ID	Treatment Results
1	The evaluated results by the authors present several fruitful movements regarding the use of biosignal decoding through Deep Learning, becoming a viable alternative to traditional treatments, especially concerning the use of robotic systems in contrast to those operated manually. The researchers also highlight that one of the main challenges is the level of sensing, as there are several commercially available options on the market that are unreliable for medical applications. Furthermore, they signal that there is little standardization of prototype evaluation protocols that compare system performance.
2	Engineers who manufacture robots from various areas were questioned about the legal and ethical awareness of these robots regarding various aspects of AI use, especially cobots, which are collaborative robots, and the safety analysis promoted for the technology. They evaluate the understanding of the safety and risks involved in the use of AI.
3	The focus of this study covers physiotherapy and clinical studies in a general way, without making the application exclusive to SCI.
4	The study suggests the application of DNNs to support BCI in combination with exoskeletons, prosthetic arms, and wearable devices to support the rehabilitation of patients. In clinical tests that proposed the addition of Brain-Computer Robotic Interfaces (BCRI) to clinical treatments,

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	patients were evaluated under the contrast of the Fugl-Meyer Assessment (FMA)[4] and Action Research Arm Test (ARAT)[5] methodologies, with gains and increments perceived in positive feedback from the intervention. The researchers also evaluated both online and offline system connectivity scenarios, obtaining robust gains in walking patterns. Additionally, the study exposes a contrast between the use of invasive and non-invasive methods for acquiring brain data, processing and categorizing it according to desired characteristics, and then classifying it and using ML patterns, thereby enabling direct and discrete control strategies for BCIs (Assistive and Rehabilitative).
5	Although there has been a good response to treatment using EES, some challenges should be considered such as the possibility of registering a small amount of brain activity in patients, risk of infection, possibility of causing local immune responses, and inducing the generation of glial scars around the electrode. Therefore, there is a possibility of reduced efficacy of the brain-spine interface system. Although this interface successfully transmits motor nerve signals from the brain to the spinal cord, the first generation of these systems cannot return sensory nerve signals from paralyzed patients to the brain.
6	According to the study, the main functional problems were related to elderly individuals with complete tetraplegia or long-term injuries. The greatest problems with independence in carrying out activities were recorded in countries with lower per capita income (GDP).
7	The study suggests reliable *in-silico* models for screening new potential therapeutics for SCI. However, although highly desirable, these models are not yet available due to the lack of comprehensive knowledge of the molecular and cellular mechanisms involved in SCI. Therefore, *in-vitro* models are still used to help understand the complex cellular mechanisms involved in SCI and identify new therapeutic targets. This model also allows for screening of new pharmacological tools and potential therapies before testing in animal models. Some *in-vitro* studies may also raise ethical and animal welfare issues.
8	The authors note the use of therapies applied to Carpal Tunnel Syndrome (CTS), a medical condition that affects nerve connections and movement of the hand and fingers. With the proposed technological application of the EasiCNCSII method, convenient and non-invasive options are identified for collecting data and identifying CTS with satisfactory performance. Furthermore, the use of mobile applications by users along with EasiCNCSII can provide low-cost universal access to medical care outside the hospital, especially in remote rural areas with limited resources and access to healthcare professionals. The authors suggest that with the application, it will be possible to promote a balanced distribution of quality medical resources that tends to improve as a more robust database of sEMG (surface electromyography) signals and other related therapy information is established.
9	The paper reports on techniques for controlling robotic devices through invasive or non-invasive methods, as well as reducing functional problems resulting from SCI through functional electrical stimulation (FES).
10	This work does not directly mention the treatment of SCI, but rather promotes an exploratory investigation of spinal posture during computer use, and observes that many individuals are unable to maintain good posture even when instructed to do so. The proposal suggests that an analysis of the influence of shoulder curvature can provide a more complete model of sitting posture. In the tests, none of the patients maintained good posture throughout the task, and two of them never regained good posture after starting computer use. Model calibration showed

[4] The Fugl-Meyer Assessment (FMA), also known as the Fugl-Meyer Evaluation Scale (EFM), was developed and introduced in 1975 by Fugl-Meyer. This scale was the first quantitative instrument for sensory-motor measurement of stroke recovery.

[5] The Action Research Arm Test (ARAT) was created to assess the recovery of upper limb function after cortical injury, and its combined use with FMA evaluations is recommended.

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	that the range of flexion and ideal posture varied between patients, aiming to provide feedback to the user through a single flexible sensor that can prevent conditions that cause harm to health.
11	The use of Lokomat, combined with different techniques, showed promising results in the treatment of people with spinal cord injury to improve their ability to walk, as well as reduce muscle spasm and improve muscle strength in patients. In addition, a more precise control of the patient's movements was achieved, which suggests a more agile rehabilitation process. Finally, the authors identified the use of neural models as promising for controlling Lokomat and other instruments used in the healthcare field as support for professionals' activities and people's mobility conditions.
12	In this article, the authors propose a hierarchical hybrid control system to restore movements through FES in patients with paralysis. The feasibility of the control system depends on the accurate connection of the nerve pathways involved in the patient's gait, which can benefit those with stroke as well as those with SCI (patients with complete and incomplete paraplegia). To do so, hierarchical hybrid control (with BCI) is suggested, allowing for coordination of the legs and the recognition of undesired effects, such as the mitigation of spasms through necessary course adjustments. However, it is noted that using FES to restore movements involves a degree of uncertainty, as patients may not be aware of what the controller is doing and what the effects will be perceived.

Source: The authors (2024).

The distinct approaches and obstacles concerning the integration, development, and application of medical and physiotherapy therapy, using cybernetic interfaces between patients of SCI and computers, bring several methods and technologies whose also specifies the legal awareness of engineers, developers and how laws and regulations bind their practice. Topics such as safety, compliance regulations, AI methods used (inductive or deductive), types of risks that AI creates and ethical approach to technology were observed. Some studies were not specific to SCI treatment but rather an analysis of roboticists and the challenges of the implication of technology matrices driven by AI and application in health.

6 DISCUSSION AND SYNTHESIS OF KNOWLEDGE

The different works discuss various methods and challenges related to cybernetic interfaces between user and computers, ML and biosignal acquisition in heterogeneous ways of application through the patients, presenting challenges for the therapeutic use of Brain-Machine Interfaces (BMIs).

When we address patient sensor issues, several in-vitro and in-silico approaches showed that invasive techniques performed better to signal acquisition rather than non-invasive, so that the researchers proposed an adaptive filter that could clean the acquired signal, in order to allow a better promotion of signals for connection with the Deep Neural Network (DNNs) (Jezernik, 2003) (Robinson et al., 2021).

Concerning the data deluge, the searches emphasize the importance for the use of medical study-cases databases, that can aim the cognitive abilities of physiotherapy professionals, who could use systems that can connect the different clouds of Big Data though AI techniques, improving the analysis and decision-making of doctors and health professionals, under a logical and synthetic way of a large volume of data that can be delivered from world-case analysis. Thereat, suggesting that this effect system results could allow the standardization of preclinical model selection and implementation for healthcare. (Pisotta et al., 2015; Kahile et al., 2021).

Some authors propose the evaluation and use of DL algorithms that have been validated under practical conditions, with prior guaranteed security of the treatment of patients. Nonetheless, these authors also highlight a pipeline where neurological signals can be acquired through digital encoders to ease the hardware and software system integration: the feature extraction could be submitted to preprocessing, leading to two possible paths for user controller movement - A. Classification (submitting to a high-level controller) or B. Regression (mapping directly to the device state); the application of AI Frameworks, like EasyAi could ease the evaluation of different measures of the algorithm (Walsh et al., 2006; Kahile et al., 2021; Dillen et al., 2022).

In the field of data-privacy and data-regulation, a probable solution was identified by the application of lightweight algorithms, which can quickly generate reports without compromising privacy of user data (Walsh et al., 2006). However, some researches identifies and addresses legal challenges about computer behavior and software artifacts, expressing concerns and suggesting that new compliance and legislation analysis is necessary in the area, assuring a better characterization of the setup for AI, Brain-Computer Interface (BCI) and Robotics, that often prioritize technological functionalities and not safety nor user knowledge or consent (Popovic et al., 2000; Van Rompaey et al., 2022).

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7 CLOSING REMARKS

The use of ML and AI techniques in support of BCIs can assist in the implementation of therapies with the application of exoskeletons and prosthetic arms, as well as wearable devices together with invasive and non-invasive methods for acquiring brain data with clinical evaluation by healthcare professionals.

Studies have identified different challenges faced by researchers due to the heterogeneity of systems, as well as the cybernetic interaction between machines with the acquisition and actuation of biosignals from patients (sensors and actuators), signaling the need to structure future initiatives to create more practical works that can develop new therapeutic research, such as creating a global database for SCI research that can apply Big Data and ML technologies, enabling a better understanding of the mechanisms and recovery treatments applied, expanding the cognitive capacity for analysis and decision-making of doctors, physiotherapists, and other healthcare professionals, supported by engineers and computer scientists, as well as analysts and system developers.

Also, the underlying systems should not serve as a subterfuge for not applying premises that ensure the security and compliance of patient data and therapies, promoting benefits beyond the availability of functionalities, always guaranteeing that information is stored in cybernetic frameworks of integrity and confidentiality.

Finally, algorithms and systems created should be primarily evaluated by metrics such as accuracy, sensitivity, specificity, False Negative Rate (FNR), False Positive Rate (FPR), and Area Under the Curve (AUC) so that performance correction and improvement of computational models can be promoted.

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