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Decision support systems for lower limb rehabilitation using electrical stimulation—A review

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ABSTRACT

This paper presents a comprehensive review of Decision Support Systems (DSS) for lower limb rehabilitation using Electrical Stimulation (ES), employing a rigorous two-part methodology. The first part involves a bibliometric analysis of articles from 1980 to 2023, while the second part is a systematic review of studies from 2019 to 2023, addressing six key research questions. The review identifies the main characteristics of DSS, such as data usage, sensitive data protection, reasoning techniques, and validation processes. It highlights the development focus on joint control systems, increasing interest in biofeedback and AI applications, and significant interest in FES-Cycling. Despite advancements, "decision support" remains in the early stages with simple architectures and limited data handling. Conversely, studies show advanced ES control models validated with neurological patients. This article emphasizes the need for sophisticated DSS that integrate data protection, reasoning methods, and patient monitoring to enhance rehabilitation outcomes and identifies significant gaps for future research.

1. Introduction

The rehabilitation of lower limb muscles is crucial for patients with neuromuscular injuries or diseases affecting mobility. Conditions such as paralysis due to stroke, knee osteoarthritis, and sarcopenia are shared among old adults, resulting in significant mobility issues and decreased quality of life [1]. These conditions often reduce patient independence, impacting their daily activities and increasing the need for long-term care. As the population ages, the prevalence of these conditions rises, emphasizing the urgent need for effective and accessible rehabilitation strategies [2].

In this context, Electrical Stimulation (ES) has emerged as a promising technique for muscle rehabilitation of the lower limbs. ES promotes muscle activations through electrical impulses, which can improve the strength and coordination of the affected limbs, facilitating functional recovery. However, the application of ES faces considerable challenges, particularly in the personalization and adaptation of treatments to meet each patient's specific needs. The variability in individual responses to ES treatments makes it essential to develop approaches that can dynamically and precisely adjust stimulation parameters, ensuring the efficacy and safety of interventions [3].

The rehabilitation programs reported in the literature show a wide variety of approaches and often depend on intrinsic patient factors such as the severity of the condition, the response to treatment, and skin composition. This diversity of approaches highlights the need for a broader information set to characterize treatments better and personalize them. Typically, rehabilitation programs involve visits to specialized clinics where electrical stimulation devices are used to adjust parameters such as intensity, pulse width, and frequency. However, these devices often lack adequate informatization and are not integrated with patients' medical records, limiting the ability for continuous monitoring and precise adjustments during treatment [4].

In this scenario, Decision Support Systems (DSS) emerge as essential tools for optimizing rehabilitation processes. DSS can integrate clinical data, stimulation parameters, and real-time feedback, providing valuable information to physiotherapists for more precise and practical adjustment and monitoring of treatments. A DSS is characterized by its ability to process large data volumes and offer healthcare professionals evidence-based recommendations. These systems can enhance decision-making by analyzing patient-specific data and clinical guidelines, resulting in more personalized and effective treatment plans [5].

The growing demand for personalized, evidence-based treatments underscores the importance of developing and implementing effective

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DSS for rehabilitation with ES. These systems can help overcome the limitations of traditional methods by providing recommendations based on extensive data and best clinical practices. Additionally, with advancements in artificial intelligence and machine learning technologies, DSS can evolve to offer more sophisticated insights, continuously adapting to changes in patients' conditions [6].

The study here reported utilizes a systematic literature review to explore DSS applied to lower limb rehabilitation using electrical stimulation. A systematic review is a rigorous methodology that identifies, evaluates, and synthesizes all relevant evidence on a topic, ensuring a comprehensive and unbiased overview of existing research [7]. The review aims to identify the characteristics of the systems developed, the data used, methods for protecting sensitive data, reasoning methods employed, and validation processes adopted. Six research questions are formulated to guide this investigation and provide a comprehensive view of the current state of research and emerging trends in this field.

This article is organized into five main sections. The second section addresses the methodology, describing the steps followed to carry out the review, detailing the keywords used, and the application of the Kitchenham and Charters [7] methodology, which supports this work. The third section presents research trends over time, extracted from the metadata of the selected articles, covering the period from 1980 to 2023. The fourth section focuses on the systematic literature review for the articles selected between 2019 and 2023, with the goal of answering the research questions defined in the methodology. Finally, the fifth section presents the study's main conclusions and points to possible directions for future research.

2. Methodology

The methodology used to develop the presented review can be divided into two main stages. Initially, an iterative search process was carried out to identify keywords that should be included and excluded from the search query. At this stage, the R Studio tool and the Bibliometrix library [8] were used to analyze the meta information of the articles. In the second stage, it was applied the methodology developed by Kitchenham and Charters [7] to create a Systematic Literature Review considering publications from the last 5 years, that is, from the beginning of 2019 to the end of 2023.

2.1. Keywords identification

The proper identification of keywords is a crucial step in conducting a literature review, especially when dealing with a multidisciplinary subject such as the development of DSS for muscular rehabilitation of the lower limbs with electrical stimulation. Nowadays online literary databases provide a set of tools that help create advanced searches, such as the use of Boolean logic and field restriction, but for some subjects it still common to find a huge number of studies unrelated to the main topic.

In our case, the high number of unrelated studies is mainly due to two factors. The first factor is related to the vast literature available on muscular rehabilitation treatments without mentioning the use of any system. The second factor is linked to the high applicability of electrical stimulation in the human body, not restricted only to the lower limbs. Furthermore, the term electrical stimulation can also be found in other areas not linked to muscular rehabilitation. Therefore, it was necessary to carefully select the keywords to ensure greater efficiency and relevance of the included studies.

The process of identifying keywords began with the definition of three central concepts that must be present in studies: "System", "Decision Support" and "Electrostimulation". These concepts served as the basis for building the initial search query, called "Query_Inclusion", comprising synonymous and equivalent terms to ensure comprehensive coverage. Table 1 provides a complete list of these terms.

Table 1
Inclusion search terms.

ID	Concept	Query with terms and synonyms
QI_01	System	"system" OR "application" OR "app"
QI_02	Decision Support	"decision support" OR "intelligent decision" OR "decision making" OR "decision-making" OR "learning system" OR "data driven" OR "data-driven" OR "artificial intelligence" OR "machine learning" OR "based reasoning" OR "control system" OR "controller" OR "closed-loop" OR "closed loop"
QI_03	Electrostimulation	"electrostimulation" OR "electric stimulation" OR "electrical stimulation" OR "electrical muscle stimulation"

Table 2
Exclusion search terms.

ID	Concept	Terms and synonyms
QE_1	Body Parts	"hand" OR "finger" OR "brain" OR "head" OR "heart" OR "chest" OR "torso" OR "arm" OR "shoulder" OR "elbow" OR "cells" OR "ankle" OR "trunk" OR "transcranial" OR "diaphragm" OR "lung" OR "pupil" OR "ganglion" OR "subcortical" OR "cortical" OR "cortex" OR "blood" OR "sacral" OR "urinary" OR "upper limb" OR "tactile"
QE_2	Treatments	"surgery" OR "cochlear implants" OR "dropped foot" OR "drop foot" OR "tremor"
QE_3	Other stimulator	"microstimulation" OR "electrotactile" OR "electrophysiology" OR "spinal cord stimulation" OR "microelectrode" OR "spinal cord stimulator"
QE_4	Not Human	"animal" OR "animals" OR "primate" OR "rats"
QE_5	Metal Construction	"ion" OR "iron" OR "energy efficiency" OR "energy consumption" OR "alumina" OR "aluminum" OR "carbon" OR "ultrasonic" OR "microstructure" OR "metal" OR "light metals"

The searches were made in the PubMed, Web of Science and Scopus databases, considering all years available on the platforms until the end of 2023. The initial search results were analyzed using the R Studio tool through the bibliometrix library. The bibliométrix library allowed a detailed analysis of the keywords most frequently used by authors, in addition to providing other relevant information, such as the journals where the articles were published.

Through these analysis, a set of keywords and periodicals were observed that were not directly related to the scope of the research, which resulted in the inclusion of several non-pertinent articles. To address this issue, it was necessary to create a new query using the exclusion keywords with the "and not" condition, thus refining the search results and removing articles not aligned with the review theme.

Query_Inclusion: QI_01 ***AND*** *QI_02* ***AND*** *QI_03*

This refinement process was iterative, carefully evaluating the selected keywords and their application in subsequent searches. Table 2 describes the concepts and search terms added to create Query_Exclusion, which includes all terms that have been removed.

Query_Exclusion: QE_1 ***OR*** *QE_2* ***OR*** *QE_3* ***OR*** *QE_4* ***OR*** *QE_5*

Finally, Query_Final represents the optimized query used in the development of this review.

Query_Final: Query_Inclusion ***AND NOT*** *Query_Exclusion*

Table 3
Research questions.

ID	Question
RQ_01	What are the main characteristics of the system architecture?
RQ_02	What data is used and how is it acquired?
RQ_03	How is sensitive data protected?
RQ_04	What are the reasoning methods used in these systems?
RQ_05	How do systems modify electrical stimulation?
RQ_06	How were the systems validated?

Table 4
Inclusion criteria.

ID	Inclusion criteria
IC_01	Studies published between 2019 until 2023 inclusive.
IC_02	Studies written in English.
IC_03	Studies that do not have a more recent version.

Table 5
Exclusion criteria.

ID	Exclusion criteria
EC_01	Studies that do not present the complete article or without access.
EC_02	Studies do not use electrical stimulation or only use computer simulation.
EC_03	Studies that do not apply electrical stimulation to the lower limbs.
EC_04	Studies that do not use computerized system.

This optimized query reduced the number of articles retrieved from the databases from 5300 to 1464, considering publications from 1980 until 2023 in the three databases. For the last five years, 2019–2023, the amount of papers decreased from 1343 to 371. This is an approximate 72% reduction in the number of articles, removing only terms that are not of interest.

2.2. Systematic literature review approach

The systematic literature review conducted followed the methodology prescribed by Kitchenham and Charters [7]. This methodology divides the review process into three phases: planning, execution and summary. In the planning phase, a detailed protocol was developed, defining research questions, inclusion and exclusion criteria.

In the execution phase, a comprehensive literature search was carried out, followed by the selection of relevant studies based on the established criteria. Finally, in the summary phase, data is extracted, synthesized and compared to generate the results of the review. The State of the Art through Systematic Review (StArt) tool [9] was used to assist in protocol management.

2.2.1. Planning

This systematic literature review aims to synthesize, elucidate and analyze decision support systems described in academic literature over the last five years. In particular, the focus is on systems developed to assist in the rehabilitation of lower limb muscles through electrical stimulation. Table 3 presents the six research questions (RQs) formulated to guide this study.

The keywords defined in Section 2.1 were then applied to the PubMed, Web of Science and Scopus databases, restricting the search to articles published between January 2019 and December 2023 inclusive. Using the tools available in online databases, a filter was applied to return only conference articles and journal articles. Additionally, survey articles were removed, ensuring that only primary studies were considered in the systematic review.

The articles selected from the referred databases were evaluated based on the criteria established in Tables 4 and 5. For an article to be accepted in the review, that is, to actually be fully read and have its information extracted, it is necessary to comply with all inclusion criteria and no exclusion criteria.

2.2.2. Execution

In the execution phase, searches were carried out in the selected databases in accordance with the protocol established in the planning phase. The search results were exported to the StArt software, which allowed efficient management of articles throughout the different stages of the review, in addition to facilitating the removal of duplicate articles.

The flow of articles throughout the selection process, from initial screening to final inclusion in the review, was documented using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) Statement and depicted in the flow diagram shown in Fig. 1.

The use of PRISMA in this study not only guarantees the transparency and quality of the review report but also contributes to the replicability of the study, allowing other researchers to repeat and validate the results presented in this systematic review [10].

During the screening phase, the titles, abstracts, and author keywords of the articles were read to determine their relevance to the main topic. The purpose of this stage was to quickly exclude articles that had no connection to the main theme. As a result, 58 articles were selected for full reading.

Among the 58 selected articles, 29 met all inclusion criteria and did not meet any exclusion criteria, thus being considered for further information extraction.

The main reasons for excluding articles were the following: first, EC2, studies that did not effectively apply stimulation, such as studies that presented computer simulation of the use of electrical stimulation without presenting a real device or system architecture. The second most common reason, EC3, was the lack of application of electrical stimulation to the quadriceps muscles, which was not aligned with the scope of the systematic review.

3. Research trends over time

This section aims to provide a bibliometric analysis of the evolution of research in the area of DSS for lower limb muscle rehabilitation with electrical stimulation. Understanding trends over time is crucial for developing future technologies, providing an overview of researched and current topics, while identifying obsolete terms or discontinued research lines.

For this bibliometric review, 1464 articles were collected from the PubMed, Web Of Science, and Scopus databases, covering the publication years from 1980 to 2023. Only one preprocessing operation was performed to remove duplicates, resulting in a total of 1048 articles for analysis. The tools used to extract information were R Studio and the bibliometrix library, while Microsoft Excel was used for adjusting and designing the charts.

The data series presented in Fig. 2 reports scientific production over the years on the topic of the review. The number of publications remained relatively low from the early 1980s until the mid-1990s, with only a few articles published annually. However, from the late 1990s onwards, research activity increased significantly, with the number of publications steadily rising each year.

At least two turning points in the number of publications can be observed in Fig. 2. The first occurred in 2007 when a minimum of 20 articles were published every subsequent year. The second turning point was 2016, when the minimum number of publications doubled to 40 articles per year. This upward trend peaked in early 2020, with a remarkable 67 publications in 2022, highlighting the exponential growth and maturation of the field. Additionally, the consistent presence of publications over the years indicates sustained interest and investment in research related to DSS for muscular rehabilitation with electrical stimulation. This growth underscores the relevance of the topic in the scientific community.

The second analysis conducted involved extracting bigrams from the abstracts of the articles. This technique, applied through natural language processing algorithms, identifies pairs of words frequently

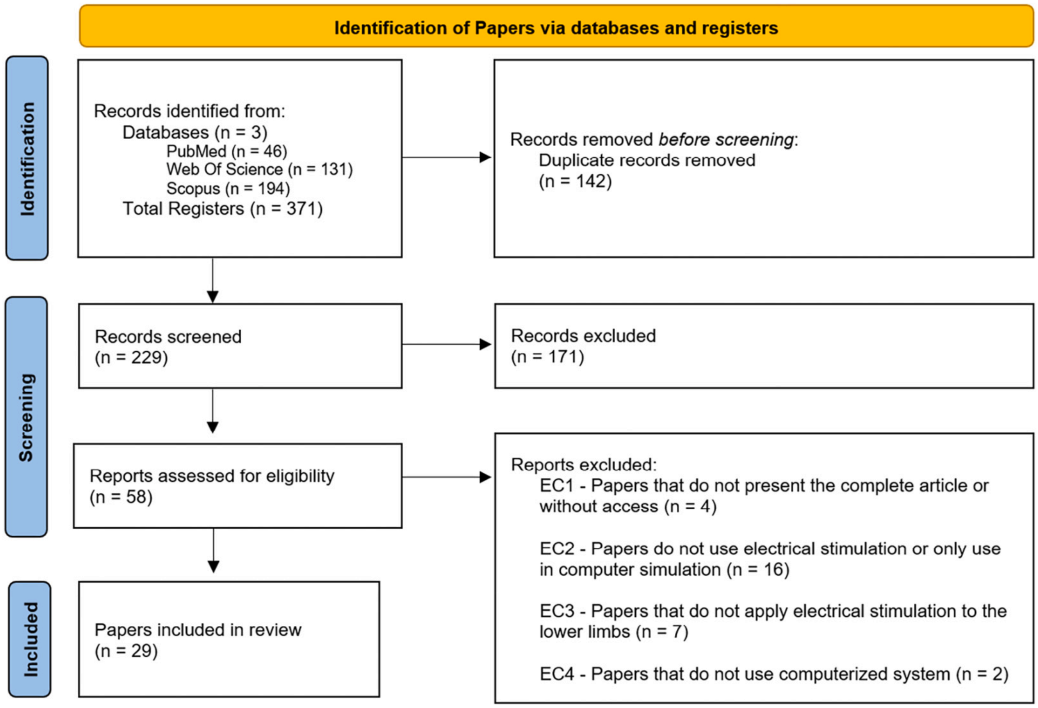

Fig. 1. PRISMA 2020 flow diagram of the systematic review..
Source: Adapted from [10]

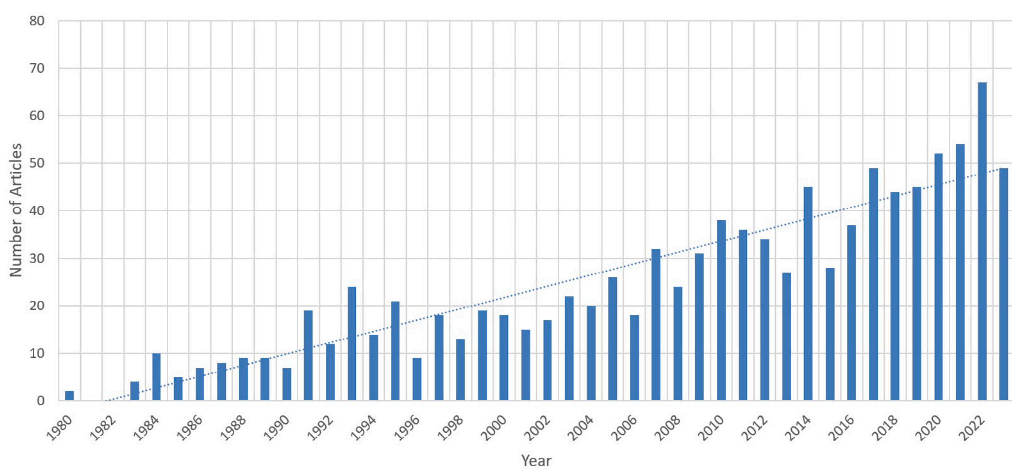

Fig. 2. Annual Scientific Production.

occurring together in texts, providing valuable insights into the main themes and concepts addressed in scientific literature.

During the bigram extraction process, irrelevant terms such as “results demonstrate“ or “error system” were removed, as they do not contribute to understanding the research topics. Additionally, terms related to electrostimulation were excluded, as all studies use this technique as part of their intervention. The aim was to highlight secondary terms associated with electrostimulation, providing a deeper insight into the concepts and themes addressed in research on DSS for muscle rehabilitation.

The analysis of the bigrams presented in Fig. 3 revealed interesting patterns in the evolution of the most frequent terms over time. The term “control system” emerges as the main and most consistent term over the years, with the first publications dating back to the early 1980s and a continuous presence until the present day. This suggests that researchers have consistently sought to control movement since the beginning of investigations.

Secondly, “muscle fatigue“ stands out, especially from 2010 onwards, indicating a growing interest in this complex topic. This rise suggests an evolution in researchers’ understanding over time, expanding the scope of investigations to consider not only movement control but also the effects of muscle fatigue in this context. This shift in focus is supported by the evolution of the term “muscle model”, which follows a similar but less intense trend.

The third most used term, “neural network”, demonstrates a constant rise over the years, with periods of stagnation interspersed. This pattern suggests computational challenges that may limit the effective use of neural networks at certain times, highlighting the need for continued development in this area.

Other notable terms include “FES Cycling“ and “Electric Motor”, which show a similar increase in frequency and are correlated. This indicates that research on muscular rehabilitation with electrical stimulation, using bicycles and exoskeletons, began to gain prominence in 2015 and continues to be one of the main research topics today.

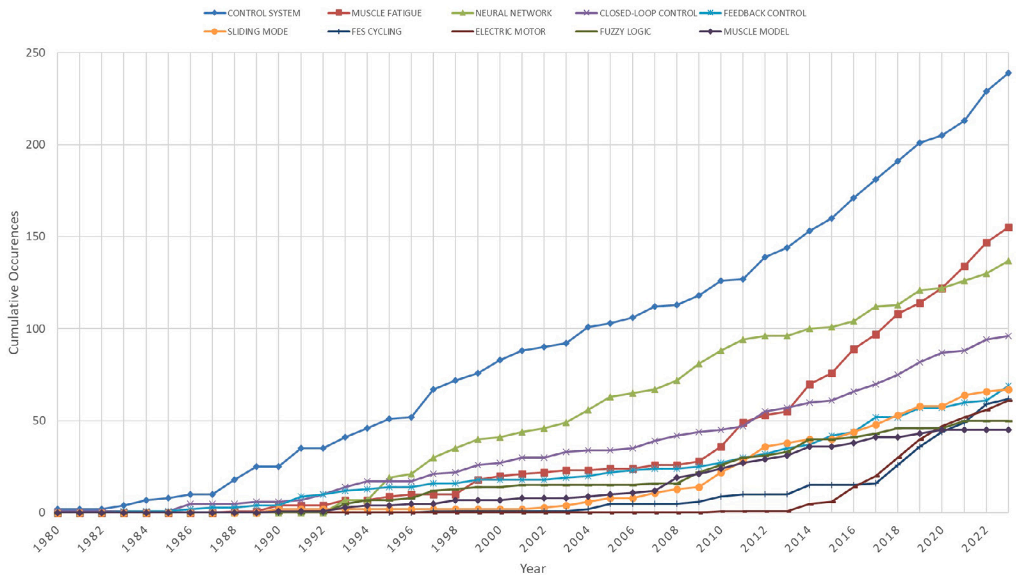

Fig. 3. Top 10 bigram terms over time.

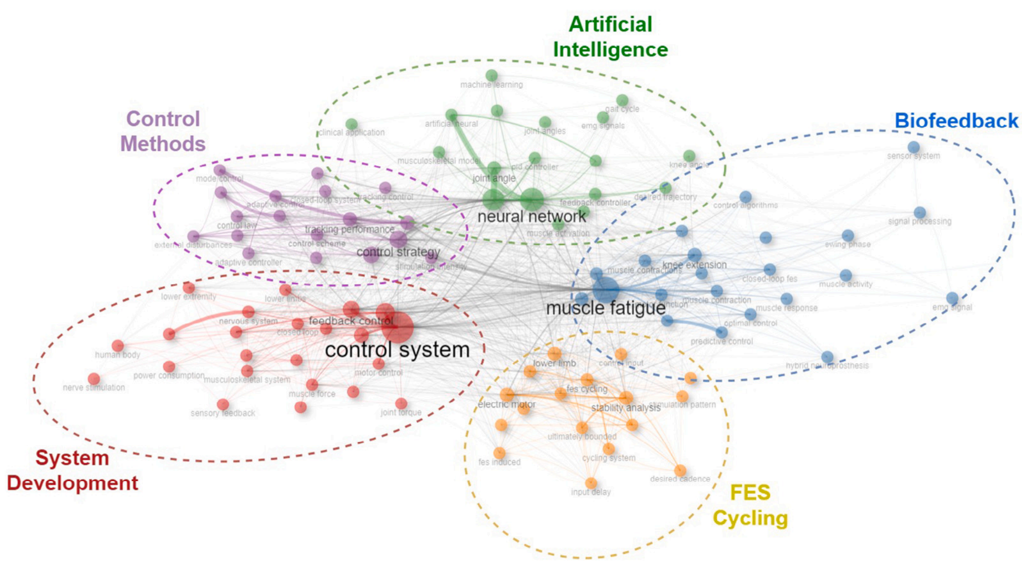

Fig. 4. Co-occurrence Network of bigram terms.

Continuing with the analysis of the bigrams extracted from the abstracts, a Co-occurrence network graph was generated. This graph was constructed based on the terms that co-occurred most frequently in the abstracts, revealing the relationships between the terms and identifying significant thematic groupings.

The Louvain algorithm was applied to identify clusters, with the number of nodes set to 100 to ensure a comprehensive analysis. This algorithm utilizes a hierarchical clustering method that recursively combines communities into a single node and performs modularity clustering on condensed graphs. The goal is to maximize a modularity score for each community.

Modularity quantifies the quality of the assignment of nodes to communities. It assesses how densely connected the nodes are within a community compared to how connected they would be in a random network. This results in groups of terms that co-occur more frequently and are more strongly interconnected, with no overlap [11].

Five distinct clusters were identified, as illustrated in Fig. 4, each representing a specific branch of study applied to systems with electrical stimulation for lower limbs rehabilitation. The central theme of each cluster was determined empirically based on the related terms included in the cluster.

- **System Development:** This cluster is centered around terms related to the development of control and stimulus systems. Includes words such as “control system“, “stimulation parameters”, “closed loop“, “stimulation patterns”, “motor control“, “power consumption”. This suggests a focus on creating and improving systems for controlling and administering electrical stimulation.
- **Control Method:** Set related to strategies and control methods to parameterize electrical stimulation given a certain objective. It includes terms such as “control strategy“, “control scheme”, “adaptive control“, “control law”, “sliding mode“ and “tracking performance”. This indicates a concern with the development of adaptive and robust control techniques to optimize the effectiveness of electrical stimulation.
- **Artificial Intelligence:** This cluster focuses on the use of artificial intelligence in research related to muscle rehabilitation with electrical stimulation. It includes terms such as “neural network“,

Table 6
Characterization of the 29 selected articles.

Ref.	Author	Year	Aim	Country	Type
[12]	Watanabe and Tadano	2019	FES Cycling	Japan	C
[13]	Obuz et al.	2019	Exoskeleton	Turkey	J
[14]	Estay et al.	2019	FES Cycling	USA	C
[15]	Ghanbari et al.	2019	FES Cycling	USA	J
[16]	Rahim et al.	2019	Exoskeleton	Malaysia	C
[17]	Cerone et al.	2019	FES Cycling	Italy	C
[18]	Sijobert et al.	2019	FES Cycling	France	J
[19]	Duenas et al.	2020	FES Cycling	USA	J
[20]	Bao et al.	2020	Exoskeleton	USA	J
[21]	Teodoro et al.	2020	FES Cycling	Brazil	J
[22]	Ricarte et al.	2020	FES Cycling	Brazil	C
[23]	Zhang et al.	2020	Knee Control	China	J
[24]	Zhang et al.	2020	Knee Control	China	C
[4]	Arcolezi et al.	2021	Knee Control	France	J
[25]	Isaly et al.	2021	FES Cycling	USA	J
[26]	Cousin et al.	2021	FES Cycling	USA	J
[27]	Aldrich and Cousin	2021	FES Cycling	USA	J
[28]	Molazadeh et al.	2021	Exoskeleton	USA	J
[29]	Rouse et al.	2021	FES Cycling	USA	J
[30]	Allen et al.	2022	FES Cycling	USA	J
[31]	Chang et al.	2022	Exoskeleton	USA	J
[32]	Nekoukar	2021	Knee Control	Iran	J
[33]	Jafari and Erfanian	2022	FES Cycling	Iran	J
[34]	Coelho-Magalhães et al.	2022	FES Cycling	Brazil	J
[35]	Popović-Maneski and Mateo	2022	FES Cycling	Serbia	J
[36]	Lyu et al.	2023	Exoskeleton	Germany	J
[37]	Wannawas and Faisal	2023	FES Cycling	England	C
[38]	Sun et al.	2023	Exoskeleton	USA	J
[39]	Ferrari et al.	2023	Exoskeleton	Italy	C

"machine learning", "artificial neural", "musculoskeletal model", and "clinical application". This suggests a growing trend of using machine learning algorithms and advanced computational models to improve muscle rehabilitation approaches.
- **Biofeedback:** This group is related to the physiological response and monitoring of biological signals during the muscular rehabilitation process. Relevant terms include "muscle fatigue", "muscle contraction", "muscle model", "signal processing", "real time", "muscle activity", and "EMG signal". These terms reflect the interest in understanding muscle fatigue and muscle activity during treatment.
- **FES Cycling:** This cluster focuses on research exploring the use of electrical stimulation using bicycles and exoskeletons. Includes terms such as "fes cycling", "electric motor", "tracking error", "stability analysis", "cadence tracking", "desired cadence", "cycling system", and "hybrid system". This cluster collaborates with the idea that this topic is increasingly on the agenda and can bring relevant benefits to muscular rehabilitation.

Analyzing bigram terms and identifying clusters provides information about the most important topics surrounding the main research topic and how they relate to each other. The clusters highlight different aspects of research, from the development of control systems and their methods to the application of artificial intelligence and the use of biofeedback. The intersection between these clusters suggests promising opportunities for interdisciplinary research and the integration of innovative approaches.

Finally, this bibliometric analysis provides a comprehensive overview of the leading research trends in DSS for lower limb muscle rehabilitation through electrical stimulation. This detailed understanding of trends over time can guide future investigations and contribute to the continuous advancement of the area, allowing the identification of knowledge gaps and opportunities for innovation.

4. Systematic literature review

This section analyzes 29 selected articles, following the systematic review methodology illustrated in Fig. 1, covering publications from 2019 to 2023. The original objective was to identify decision support systems designed specifically to assist physiotherapists in electrostimulation-based rehabilitation. However, the review revealed that none of the articles explicitly described such systems. Instead, all selected studies focused exclusively on electrostimulation control systems, typically automated solutions that manage stimulation parameters without active physiotherapist involvement or real-time monitoring of clinical progress.

A critical distinction between DSS and control systems lies in their purpose and operational complexity. Control systems automatically adjust predefined parameters to achieve specific physiological outcomes, generally independent of direct clinician interaction. In contrast, DSS integrates broader functionalities such as secure patient data management, physiological monitoring in real-time, and reasoning methods to actively support clinical decision-making processes. In addition, DSS typically has intuitive interfaces that allow healthcare professionals to monitor patient progress, interpret analytical insights, and make informed therapeutic adjustments.

The selected articles mainly address three main themes: 17 focused on FES Cycling, 8 on Exoskeleton and 4 on Knee Control. Regarding the type of publication, 8 are from conferences and 21 are journal articles. The corresponding authors come from various countries, with the United States leading with 12 articles, followed by Brazil with 3. Italy, France, Iran and China contributed 2 articles each, while Japan, Turkey, Malaysia, Serbia, Germany and the United Kingdom contributed with 1 article each. Table 6 presents this detailed information, with *J* indicating journal articles and *C* for conference papers, along with the respective references and authors.

FES-Cycling is a therapeutic approach that combines the use of stationary bicycles with electrical stimulation of the muscles of the lower limbs. Generally, the quadriceps, hamstrings and gluteal muscle groups are stimulated in a coordinated sequence to generate a positive crank cycle. This method presents improvements in the cardiorespiratory, neuromuscular and skeletal system, such as increased muscle mass, improved blood circulation and reduced bone loss. However, these improvements may be mitigated due to the possibility of accelerated fatigue or physical exhaustion [40].

Generally, bicycles or tricycles have a motor that also assists the movement, allowing patients with little or no capacity for voluntary movement in their legs to perform the exercise. This practice is carried out indoors, generally in a stationary system with a focus on rehabilitation, however, it is currently possible to find competitions that use this system and demonstrate new technologies, such as the Bike Race - Cybathlon.[1]

The main challenge of FES-Cycling is to coordinate electrical stimulation with the bicycle motor to maintain an effective and comfortable cadence for the patient without excessive fatigue. This synchronization is often done through complex mathematical models and the use of sensors to monitor cadence and adjust the electrical stimulus and motor accordingly. In the United States, the group led by researcher Warren Dixon was responsible for all 8 publications on FES-Cycling that were selected for this systematic review. The work of this group has contributed significantly to the advancement of knowledge about FES-Cycling and its potential in lower limb rehabilitation.

Exoskeletons represent an important innovation in the area of rehabilitation, designed to help people with motor disabilities regain mobility and independence. These devices consist of external mechanical structures equipped with motors, sensors and control systems, designed to be worn around the joints of the human body, providing support and assistance during movement. Its main objective is to offer additional help to people with physical disabilities, such as spinal cord injuries, strokes or musculoskeletal disorders [41].

The selected studies address an exoskeleton model that incorporates the application of electrical stimulation to muscles to aid movement. This technique, also known as hybrid exoskeletons or FES exoskeletons, aims to provide a more effective, safe and robust rehabilitation therapy. It compensates for the lack of strength in muscles stimulated with the motor to produce movement, similar to FES-cycling.

Hybrid exoskeletons for lower limb rehabilitation generally have motors in the hip and knee joints, focusing on movements such as lifting the leg while sitting in a chair, getting up from a chair or walking. However, as in the case of FES-cycling, the biggest challenge is coordinating the stimulator and the motors together to produce the necessary movement, without causing excessive fatigue or discomfort to the patient. For more complex movements, such as walking, the challenge can be even greater, requiring a more sophisticated control system.

Knee controllers represent a simpler approach compared to other rehabilitation technologies such as FES Cycling and exoskeletons. In this approach, no motors are used, only FES stimulation is used to control the knee joint. Generally, electrical stimulation is applied only to the quadriceps, aiming at the movement of lifting the leg. Thus, the system needs to calculate the stimulation parameters to perform the movement, aiming to increase the range of movement or sustain repetitions without excessive fatigue.

In addition to offering a more traditional rehabilitation solution, knee control can be seen as a proof of concept for other applications, such as exoskeletons. This simplified approach allows the implementation of new technologies in a basic version, which can then be scaled to more advanced applications. An example is the addition of electromyography sensors to monitor muscle fatigue in real-time.

Although none of the analyzed articles explicitly presented a decision support system for electrostimulation treatment, the three topics explored (FES-Cycling, exoskeleton, and knee controller) highlight important advancements in muscle rehabilitation that are closely related to the development of information systems. These technologies address key challenges such as coordination of stimulation, fatigue management, and movement optimization, which lay the groundwork for further exploration and potential integration of more comprehensive systems in rehabilitation practices.

4.1. RQ_01: What are the main characteristics of the system architecture?

Most of the reviewed studies do not provide a precise description of the adopted system architecture, mentioning multiple devices and systems without clearly explaining their interactions. Instead, they typically mention a series of devices connected by cables to a computer, where processing is performed primarily in MATLAB/Simulink or in-house developed software, with few additional details. These devices range from encoders to measure bicycle cadence, power meters and acquisition boards, especially in studies related to FES-cycling. Furthermore, it is notable that the most commonly used stimulation machine was the Hasomed RehaStim.[2]

However, three studies stand out for proposing systems that are not limited to cable connectivity and present a more unified approach.

Study [17] proposes a modular systems architecture composed of two sets of wireless modules. One module is responsible for signal acquisition, while the other represents a stimulator machine. These modules communicate via WiFi to a multiplatform software developed with the Qt framework in C++. While this approach allows flexibility as the modules can be apply to multiple regions, it also brings with it significant technological challenges for the control system.

Study [22] describes a modular architecture based on the Robot Operating System (ROS), representing a more structured approach compared to other studies. The modular part of the architecture allows the acquisition of signals and the use of different types of sensors. In the case analyzed, it was implemented with an IMU motion sensor. The rest of the architecture consists of a portable computer and a stimulator, both connected by cables.

Study [34] deserves attention as it provides a more detailed description of its system architecture. Using an electronic board, this study establishes communication with an Android mobile application via Bluetooth. However, it remains unclear how the data is subsequently transferred for offline processing. Additionally, the study incorporates a power meter that transmits data via Bluetooth to a computer, but without details about its complete integration into the overall system.

In summary, while most studies do not provide a detailed description of the system architectures used, there is a trend towards wired connectivity to a computer for data processing, with some mention of wireless communication for data transmission. Moreover, the lack of details on how collected data is stored offline and integrated into the global system remains a common gap in the studies reviewed.

The typical expected DSS architectures from related healthcare applications, such as diabetes management platforms [42], are characterized by higher computational complexity and more robust integration capabilities. These DSS frameworks commonly include secure modules for real-time sensor data acquisition, integration of extensive patient historical records, secure storage of sensitive clinical information, and advanced analytical reasoning methods. Importantly, these systems provide intuitive interfaces for continuous engagement between patients and healthcare providers, supporting real-time feedback and iterative treatment adjustments.

Translating these sophisticated DSS architectures into electrostimulation-based rehabilitation contexts would necessitate similar capabilities: systematic integration of diverse sensor inputs (e.g., electromyography, inertial sensors), robust and secure data management protocols, clinician–patient interaction interfaces, and advanced analytical reasoning methods to facilitate personalized and adaptive therapy. Addressing the gaps identified in current research, particularly the lack of continuous clinical oversight and integration from session to session, underscores the importance of developing more comprehensive system architectures capable of supporting ongoing clinical decision-making and sustained rehabilitation outcomes.

[1] https://cybathlon.ethz.ch/en/event/disciplines/fes

[2] https://hasomed.de/produkte/rehamove

Table 7
Data acquisition tools used in selected studies.

Ref.	Data used	Acquisition tools
[12]	Crank angle (EMG data defined stimulation patterns in prior study)	2 IMUs sensors
[13]	Knee angle	Encoder
[14]	Crank angle, velocity and acceleration and power	Encoder and power meter
[15]	Crank angle, velocity and acceleration and power	Encoder and power meter
[16]	Knee angle (for validation only)	Cameras
[17]	Knee angle	Electronic goniometer
[18]	Thigh angle	2 IMU sensors
[19]	Crank angle, velocity and acceleration and power	Encoder and power meter
[20]	Knee angle	Encoder
[21]	Crank angle, velocity and acceleration	Electronic goniometer and IMU sensor
[22]	Crank angle	1 IMU sensor
[23]	Knee angle	Electronic goniometer
[24]	Ankle and knee angle and rectus femoris EMG	Angle sensor and myoeletronic sensor
[4]	Knee angle	Electronic goniometer and IMU sensor
[25]	Crank angle, velocity and acceleration and power	Encoder and power meter
[26]	Crank angle, velocity and acceleration and power	Encoder and power meter
[27]	Crank angle, velocity and acceleration and power	Encoder and power meter
[28]	Knee and hip angle	2 Encoders
[29]	Crank angle, velocity and acceleration and power	Encoder and power meter
[30]	Crank angle, velocity and acceleration and power	Encoder and power meter
[31]	Knee and hip angle, leg force and angular displacement	2 Encoders, force sensor and treadmill
[32]	Knee angle	2 IMUs sensors
[33]	Crank angle	Encoder
[34]	Crank angle, velocity and acceleration and power	Encoder and power meter
[35]	Crank angle	Encoder
[36]	Body motion capture, motor torque	Torque sensor and cameras
[37]	Crank angle	Encoder
[38]	Knee angle, force, motor torque	Encoder, dynamometer and torque sensor
[39]	Motor torque, knee angle, rectus femoris EMG	Encoder and EMG sensor

4.2. RQ_02: What data is used and how is it acquired?

A diverse set of sensors and tools were used in the selected articles to collect crucial data for controlling electrostimulation. In some cases additional data for validation were also collected that were not used in the control. Table 7 seeks to summarize the information found.

As can be seen from Table 7, most studies rely on joint angles to guide electrostimulation control, with the knee joint being the most common among them, although the thigh, ankle, and hip angles were also found to be used. For FES-Cycling studies, except for articles [17, 18], all studies use crank angles. It can also be observed that all studies were using some type of joint angle.

Given that the majority of studies focus on FES-Cycling and employ crank angle, the most common acquisition tool is the encoder, which also measures bike speed and acceleration. Second, it is noticeable that IMU sensors are increasingly gaining space in this research area, as well as electronic goniometers, which can be seen as prototypes of IMUs in this use case. This is due to the fact that many of these IMU sensors, despite having accelerometers and gyroscopes inside, are used to convert their data into angles, a function fulfilled with precision by electronic goniometers.

Finally, EMG sensors were also seen, which are important for assessing muscle activity and are related to fatigue. However, only 2 articles use this data, both collecting from the rectus femoris muscle.

4.3. RQ_03: How is sensitive data protected?

None of the selected studies explicitly addressed or detailed the strategies employed for data storage, security, or protection of sensitive patient information, revealing a significant and concerning gap within the current research field. Even studies mentioning offline data usage for training machine learning algorithms failed to specify methods or precautions related to data security and privacy, leaving unanswered critical questions regarding the ethical and practical implications of data handling within these systems.

The absence of clearly defined mechanisms for protecting sensitive patient data raises substantial concerns regarding patient privacy and the broader ethical implications in clinical applications. Rehabilitation systems utilizing electrical stimulation typically collect detailed personal health information, including biometric data, physiological responses, and treatment performance metrics, which necessitate robust confidentiality measures. Without appropriate protocols such as encryption, data anonymization, secure storage, and informed consent management, these systems remain vulnerable to breaches, potentially undermining patient trust, clinical acceptance, and adherence to regulatory standards like the General Data Protection Regulation (GDPR) or Health Insurance Portability and Accountability Act (HIPAA).

Moreover, inadequate data protection strategies significantly limit the integration of these rehabilitation systems within existing healthcare infrastructures, especially concerning interoperability with electronic medical records and institutional data management platforms. Such limitations not only hinder clinical adoption but also restrict future advancements toward comprehensive Decision Support Systems (DSS), which inherently rely upon secure, extensive data integration and exchange capabilities. Thus, addressing data protection explicitly in future studies is critical to advancing these rehabilitation technologies into clinically viable and ethically sound solutions.

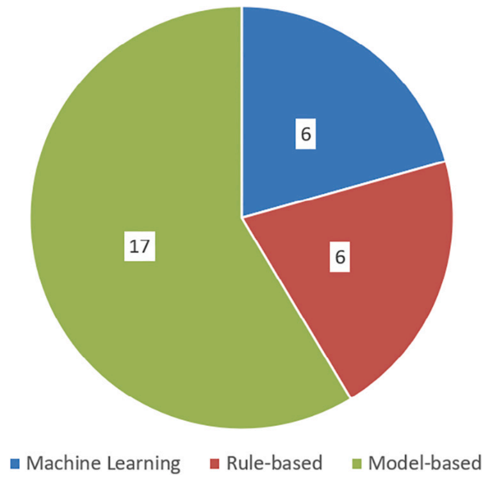

Fig. 5. Reasoning methods of the selected articles.

4.4. RQ_04: What are the reasoning methods used in these systems?

As mentioned previously, selected studies do not explicitly describe a decision support system, but rather stimulation control systems that inherently incorporate specific reasoning methods to adjust stimulation parameters. Although these methods were not consistently or explicitly labeled as reasoning methods, they can be categorized into three distinct approaches: model-based, rule-based, and machine learning. Fig. 5 illustrates the distribution of these methods among the reviewed articles.

The model-based reasoning approach was predominant, employed by 17 out of the 29 reviewed articles. This method involves using mathematical or computational models that simulate muscle dynamics, joint movements, or physiological responses to determine optimal stimulation parameters. Typically implemented within closed-loop control systems, model-based reasoning integrates real-time sensor data — such as encoder outputs for joint angles, IMUs for motion tracking, or power meters for performance metrics — into predictive mathematical models. These models enable dynamic adjustments of electrical stimulation to achieve precise movement control and mitigate issues like muscular fatigue or irregular movements. Despite its widespread use, model-based methods require highly accurate system modeling and parameter estimation, which can pose challenges due to patient-specific variability and complex biological responses.

Six studies utilized rule-based reasoning methods to manage stimulation control. Rule-based systems generally involve predefined sets of logical conditions or thresholds that directly dictate stimulation activation and deactivation. Such methods are less computationally demanding and typically rely on simple decision rules based on easily measurable variables. For instance, several FES-cycling studies employed rules triggered by specific crank angles or velocity thresholds, activating and deactivating stimulation accordingly. Despite their simplicity and ease of implementation, rule-based methods offer limited adaptability, as their static rules are not capable of addressing complex physiological variations or adaptive needs across diverse patient populations.

Additionally, six studies incorporated machine learning algorithms, representing an emerging and promising approach within this field. Machine learning methods identified in the reviewed literature include neural networks, reinforcement learning, and other adaptive algorithms. Unlike the previously described methods, machine learning techniques have the potential to recognize more subtle and complex patterns in patient response, enabling adaptive control beyond simple on–off activations. Notably, some studies applied machine learning merely for binary activation decisions, while more advanced implementations adjusted parameters such as pulse width, amplitude, and frequency dynamically. Although machine learning methods exhibit substantial promise for personalized treatment, their clinical applicability remains limited due to the need for large and diverse datasets, computational complexity, and the necessity for extensive validation across different patient profiles. Therefore, despite its promising capabilities, this reasoning method is still emerging in the research field, presenting significant opportunities for future exploration and clinical validation.

Table 8
Study participants by type.

Subjects	FES cycling	Exoskeleton	Knee control	Total
Healthy	61	15	21	97
Neurological Conditions	18	7	15	40
Total	79	22	36	137

4.5. RQ_05: How do systems modify electrical stimulation?

The studies reviewed demonstrate a variety of approaches to modifying stimulation parameters. The majority of studies focused on adjusting a single parameter, with 22 of them varying only one. Specifically, 16 of these studies chose to vary the pulse width, while 6 opted to vary the intensity, which refers to the pulse's amplitude. It is worth noting that in some articles, the term "intensity" was also used to describe the total applied force, as exemplified by "intensity was altered by both pulse width and pulse amplitude".

Three studies stood out for modifying more than one parameter. Studies [34,39] simultaneously altered two parameters in their control systems: pulse width and intensity. Only one study, [32], was notable for varying all three parameters, including frequency. This particular study questioned the fact that most articles modified only pulse width and aimed to demonstrate the feasibility and effectiveness of the control system by using all three parameters.

In contrast, four studies [16–18,37] did not clearly describe parameter adjustments or explicitly stated that no dynamic variation was used. These systems typically relied on the activation and deactivation of stimulation using fixed and predefined values.

Overall, the analysis emphasizes that the main strengths of these systems lie in adaptive automatic control and the emerging use of advanced biofeedback and artificial intelligence techniques, which allow real-time adjustments to patient muscle responses.

4.6. Q_06: How were the systems validated?

The validation of systems is a crucial step in the development of new technologies, as it provides a means of measuring the effectiveness and safety of these systems before their clinical implementation. Upon analyzing the selected articles, a total of 137 subjects who participated in the studies were identified, with 40 of them having neurological conditions, primarily total lower limb paralysis. Table 8 illustrates the distribution of subjects grouped by type. Despite there being more than twice as many studies on FES-Cycling compared to Knee Control, both approaches involved a similar quantity of neurological participants.

Each type of study varied significantly in participant numbers. Study [13], involving exoskeletons, tested its system on 10 healthy participants and 3 with neurological conditions, representing the highest participant count among analyzed studies. Study [32], focused on knee control, evaluated its system's performance exclusively on 10 participants with neurological conditions, emphasizing the clinical applicability of their system in addressing neurological deficits. Meanwhile, study [39], which dealt with FES-Cycling, tested the system exclusively on healthy participants, highlighting the preliminary stage of its clinical translation. The majority of remaining studies involved fewer participants, typically averaging 4 healthy individuals and at least one participant with neurological conditions.

Several studies reported significant clinical findings and potential impacts, reinforcing their clinical relevance. For instance, study [13] validated their closed-loop neuromuscular stimulation control system, demonstrating robust performance despite unknown input delays in muscle dynamics, a common clinical issue in rehabilitation contexts. Similarly, the work by [32] demonstrated the feasibility and clinical effectiveness of simultaneously modulating multiple stimulation parameters, providing improved outcomes for motor function and patient comfort during therapy sessions. These specific clinical validations highlight not only the potential impact of advanced electrostimulation systems but also underscore the importance of conducting rigorous trials with clinically meaningful outcomes.

Despite these promising results, six studies conducted their validation with only a single participant [14,17,18,22,37], and [34], emphasizing the preliminary stage of many systems. Although initial results from single-participant validations can be insightful regarding feasibility, these limited-scale studies highlight a clear need for broader, multicenter clinical validations to establish robust evidence on clinical efficacy, generalizability, and long-term rehabilitation impacts.

5. Conclusions

This document presented a review derived from a rigorous methodology composed of two parts. The studies extracted from the three databases – PubMed, Web of Science, Scopus – aimed to develop systems to improve muscular rehabilitation treatment of the lower limbs through electrical stimulation. The first part of this review focused on carrying out a bibliometric analysis of articles extracted from 1980 to 2023. Meanwhile, the second part involved a systematic review, aiming to address six main questions and provide detailed information on the current development of systems in this field. For this second part, a more recent period was considered, from 2019 to 2023.

The bibliometric review demonstrated how search terms were interconnected over the years, revealing current trends in the most relevant topics. From the review, stand out the increase in the number of publications on the topic, indicating a growing scientific interest. The most prominent topics were categorized into four distinct groups.

The first highlights the consistent focus from the beginning on developing systems that adapt stimulation to control a specific joint. The second concern is biofeedback, a topic that is increasingly being discussed, probably because it is more viable than years ago. Likewise, the application of artificial intelligence is showing a significant increase. Finally, it was noticeable in the bibliometric analysis that there is a big scientific interest in FES-Cycling for rehabilitation of the lower limbs.

The systematic literature review was conducted to understand the proximity of the systems presented by the selected articles to decision support systems. One of the main results highlighted that the term "decision support" is still in its early stages for systems adopting lower limb electrostimulation. No system explicitly describes a decision support system, and no article addressed how data is stored or how sensitive data is managed. The system architecture presented, when mentioned, are generally simple, without cloud connectivity or interoperability.

However, several reviewed studies were able to control electrostimulation through complex models and validate with patients with neurological conditions, demonstrating maturity in the scientific process for clinical validation. Furthermore, current studies applying machine learning algorithms to control stimulation were found, although some studies only turn stimulation on and off without changing parameters, demonstrating the application of new technologies with future development prospects.

Finally, it is possible to say that the DSS with the objective of helping physiotherapists to construct treatments with electrical stimulation for rehabilitation of the lower limbs is a recent topic, worthwhile to be explored, with little material in the area of information systems. Moreover, there is a broad and consolidated scientific foundation on joint control and parameter adaptation strategies to improve lower limb rehabilitation.

CRediT authorship contribution statement

Tiago Franco: Writing – original draft, Methodology, Investigation, Conceptualization. **Pedro Rangel Henriques:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Paulo Alves:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Maria João Varanda Pereira:** Writing – review & editing, Supervision, Methodology, Conceptualization.

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Declaration of competing interest

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Data availability

No data was used for the research described in the article.

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