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A SYSTEMATIC APPROACH TO REVIEWING CONTROL STRATEGIES IN LOWER LIMB EXOSKELETONS: METHODOLOGY AND INSIGHTS

Nasiru Adamu Marafa

Adriano Almeida Gonçalves Siqueira

University of São Paulo, São Carlos School of Engineering, São Carlos-SP, Brazil
nasirmarafa@usp.br, siqueira@sc.usp.br

Abstract. Lower limb exoskeletons have emerged as transformative technologies with profound applications in fields such as, human augmentation, mobility assistance and rehabilitation. In light of their increasing potentials, gaining a comprehensive understanding of the diverse control strategies applied to these exoskeletons is crucial for researchers, engineers, and healthcare professionals. This paper presents a review methodology for scientific investigations, by systematically investigating control strategies for lower limb exoskeletons, as a case study. The methodology is developed on two main axis: (1) on x-axis is the commercial analysis, and (2) on y-axis is the academic publications analysis. To ensure inclusivity and comprehensiveness for academic publications inclusion, an exhaustive search is conducted across an array of databases, scholarly journals, conference proceedings, and documents are selected based on defined inclusion and exclusion criteria. In this scenario, four (4) scientific research databases are selected: Web of Science, Scopus, PubMed and IEEE Xplore. The secondary analysis of the methodology returned 172 documents from Web of Science, 204 from Scopus, 32 from PubMed and 92 from IEEE Xplore. For the Web of Science and Scopus results, analyses of 5 top: (a) Most relevant, and (b) Most cited papers are presented. Furthermore, to relate similar projects in bibliometric analysis, VOSviewer tool is used for the Countries Co-authorship and Authors Keywords Co-occurrence analyses. Therefore, the developed methodology can serve as a dependable framework for organizing and synthesizing the extensive corpus of literature on this and other research topics, guaranteeing the reliability and impartiality of the investigation process.

Keywords: Review Methodology, Lower Limb Exoskeleton, Control Strategies, Robotics, Rehabilitation.

1. INTRODUCTION

For many decades, lower limb exoskeletons, which are the remarkable fusion of robotics and wearable technology for lower limbs application, have emerged as transformative solutions with immense potentials to enhance human mobility, rehabilitation and quality of life. Their design and development have extended beyond the boundary of only assisting people with mobility impairments such as in Xu *et al.* (2022), Rehman *et al.* (2016), Yugan *et al.* (2014) and Zhang *et al.* (2013), but also for a wide range of areas, ranging from assisting workers in physically demanding jobs Chen *et al.* (2019), to augmenting human capabilities in various settings Chen *et al.* (2018), Al-Shuka *et al.* (2019). Scientific investigations on robotic exoskeletons have yielded many products in commercial space and outstanding ideas in scientific databases.

The history of the design and development of powered exoskeletons dated back to 1965-1971, when the General Electric Research (Schenectady, United States) developed the first powered exoskeleton for human force augmentation, dubbed "Hardiman". The machine was intended to allow the wearer to lift loads of 680 kg with ease, however unsuccessful to operate with a user in it Dollar and Herr (2008). In 1969, the first pneumatically powered exoskeleton intended for rehabilitation application was developed at Mihailo Pupin Institute (Belgrade, Serbia), and also at the University of Wisconsin-Madison in the United States in the early 1970s Huo *et al.* (2016). In recent times, research on the design, development and control of robotic exoskeletons have gained a huge space in the literature, and various products have been developed in commercial space for various applications, such as () developed for augmentation application and (HAL Hybrid Assistive Limb, designed by Cyberdyne of Japan) (REX, developed by Rex Bionic of New Zealand) developed for rehabilitation application. However, to design or use these devices effectively, understanding control strategies for lower limb exoskeletons play a pivotal role for researchers, engineers, and healthcare professionals.

Although, there are many attempts in the literature to design control systems for lower limb exoskeletons, such as in Chen *et al.* (2019), Li *et al.* (2018b), Narayan *et al.* (2023), Peng *et al.* (2021), Shushtari *et al.* (2022), Sacchini *et al.* (2022), Sharifi *et al.* (2022), Sun *et al.* (2022), Wang *et al.* (2022), Wei *et al.* (2021), Xu *et al.* (2020), Xu *et al.* (2022), and Zhang *et al.* (2022), the diversity and complexity of these control strategies reflect the multifaceted challenges and opportunities presented by this burgeoning field. An effective control strategy therefore must seamlessly integrate sensor inputs, adjust to user intentions, environmental conditions, and ensure safety and comfort. As researchers, engineers, and healthcare professionals seek to unlock the full potentials of lower limb exoskeletons, a systematic literature review to understanding, evaluating, and evolving these control strategies becomes essential.

In this work, a review methodology for scientific investigations is presented, by systematically investigating control strategies for lower limb exoskeletons, as a case study. A systematic literature review is considered as the scientific research method that brings together relevant studies on a formulated question, by using keywords and literature databases as sources and means of *identification*, *selection* and *systematic analysis*, in order to perform a critical and comprehensive literature review analysis Marafa *et al.* (2022), Dewey and Drahota (2016) and Mariano *et al.* (2017). Therefore, the methodology is developed on two main axis: (1) on x-axis is the commercial analysis, which investigates the control strategies applied to commercial lower limb exoskeletons, and (2) on y-axis is the academic publications, which investigates the state-of-the-art, challenges and opportunities related to lower limb exoskeletons from scientific databases.

However, to ensure inclusivity and comprehensiveness for academic publications inclusion, an exhaustive search is conducted across four (4) scientific databases: *Web of Science*, *Scopus*, *PubMed* and *IEEE Xplore*, and documents are selected based on defined inclusion and exclusion criteria. Results of the secondary analysis from *Web of Science* and *Scopus* databases are further analyzed for the 5 best: (a) Most relevant, and (b) Most cited papers respectively, while, *VOSviewer* tool is used in bibliometric analysis for the Countries Co-authorship and Author Keywords Co-occurrence analyses. Therefore, it is important to note that, all the results discussed and presented in this work were collected on 20th October 2023, as they might change with time.

2. THE PROPOSED REVIEW METHODOLOGY

in this work, the proposed methodology is designed to focus on two main axis: (1) on x-axis is the Commercial Analysis, which reviews the control strategies applied to commercial lower limb exoskeletons, and (2) on y-axis is the Academic Publications Analysis, which reviews the control strategies applied to lower limb exoskeletons from academic publications that are available in accredited sources. Therefore, the methodology strictly considered the following sequence of steps: (a) *Problem Formulation*, (b) *Commercial Analysis* \cap (c) *Academic Publication*, (d) *Database Selection*, (e) *Keywords Selection*, (f) *String Construction*, (g) *Document Collection*, (h) *Bibliometric Analysis*, (i) *Critical Analysis* and (j) *Gaps Identification* Fig. 1. Therefore, the review on control strategies for lower limb exoskeletons is conducted systematically following this sequence of steps.

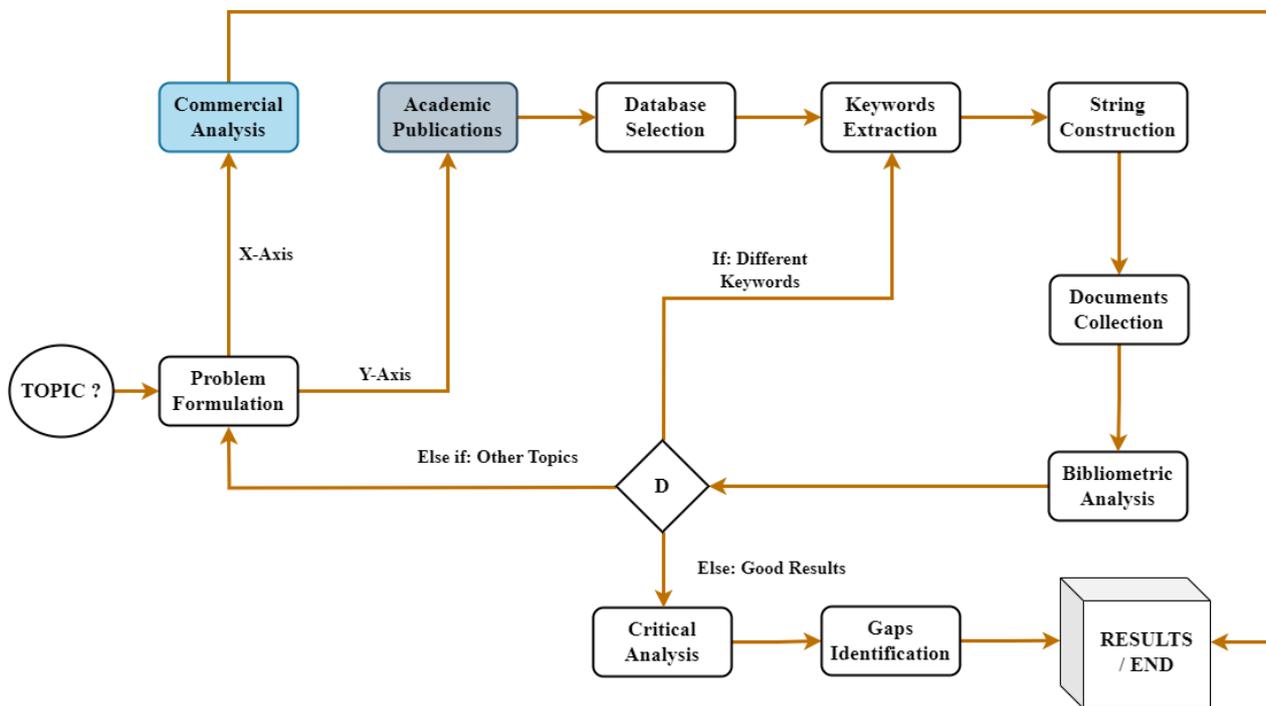


Figure 1. The Proposed Review Methodology for Scientific Investigations

3. PROBLEM FORMULATION

This is perhaps the first and the most important step of the proposed methodology. In this case, the topic to be investigated is clearly and precisely defined, in order to have a better understanding of its nature and work towards finding an effective solution. Therefore, the general and specific objectives of the research are stated in clear terms objectively. For the case study of this work, the problem was defined and formulated as: "A systematic Approach to Reviewing Control Strategies in Lower Limb Exoskeletons: Methodology and Insights".

4. COMMERCIAL ANALYSIS

In this step of the methodology, the control strategies applied to commercial lower limb exoskeletons are analyzed. Results from different companies around the world showed various control strategies for different applications. However, it was noted that, the choice of a particular strategy depends not only on the specific application, but also on user's needs and complexity of the exoskeleton system. Many modern exoskeletons in commercial arena incorporate a combination of these control strategies to provide a balance between natural movement, adaptability and safety. It was also observed that, in recent time, more attention is been given to rehabilitation application. Some of the lower limb exoskeletons found in commercial space include: (a) EksoRN, (b) PhoeniX, (c) Angel Leg, (d) HAL (Hybrid Assistive Limb), (e) Walk-On Suit, (f) Atalante, (g) Roki, (h) ReWalk, (i) ExoAtlet II, and (j) Rex, see Fig. 2. However, Tab. 1 contains information on these exoskeletons and Tab. 2 outline some of the observed sensors generally used for exoskeletons design and development.

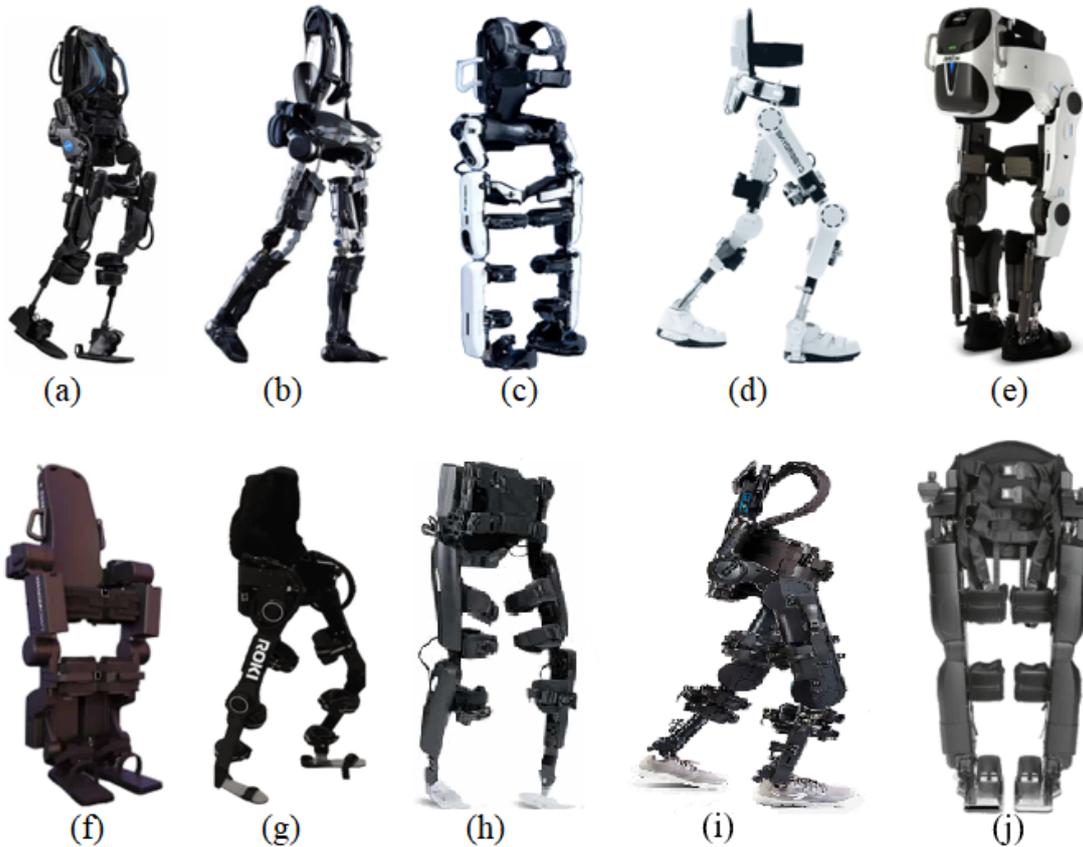


Figure 2. Commercial Lower Limb Exoskeletons Developed by Different Companies Around the World

Table 1. Control Strategies in Lower Limb Exoskeletons for Rehabilitation Applications from Commercial Analysis

	Exoskeleton	Company	Control Strategy	Main Target
(a)	EksoNR	Ekso Bionics, (USA)	Adaptive Control	ABI, S, MS and SCI
(b)	PhoeniX	SuitX, (USA)	Dynamic Control	Undergoing Testing
(c)	Angel Leg	Angel Robotics, (South Korea)	User's Intent	WTOE, Rehabilitation
(d)	HAL	Cyberdyne, (Japan)	Dynamic Control	SCI, TBI, CD
(e)	Walk-On Suit	Angel Robotics, (South Korea)	Trajectory Tracking	Complete Paralysis
(f)	Atalante	Wandercraft, (France)	Dynamic Control	Reh., Self Balancing
(g)	Roki	Roki Robotics, (Mexico)	RF Control	Rehabilitation
(h)	ReWalk	ReWalk Robotics, (Israel)	Kinematic Control	SCI
(i)	ExoAtlet II	ExoAtlet (Luxembourg)	Adaptive Control	SCI
(j)	Rex	Rex Bionics, (New Zealand)	Joystick-Based	RAP / SCI

In Table 1: S stands for Stroke, ABI for Acquired Brain Injury, MS for Multiple Sclerosis, SCI for Spinal Cord Injury, RAP for Robot-Assisted Physiotherapy, TBI for Traumatic Brain Injuries, CD for Cerebrovascular Diseases, WTOE for Walking Training Orthopedic Exercise and RF for Radio Frequency.

Table 2. Sensors Commonly Used for Exoskeleton Feedback in Control Strategies

S/N	Sensor	Position	Function
1	Force Sensors	Joints/Footplates	Measure forces and torques applied at the user-exoskeleton interface
2	Pressure Sensors	Footplates/Insoles	Detect changes in pressure distribution during walking and standing
3	sEMG Sensors	User's Skin Surface	Measure the electrical activity of muscles
4	EEG Sensors	User's Head	Measure the human intent
5	Encoders	Joints	Measure joint angles and positions
6	Ultrasonic/Infrared Sensors	Frames	Obstacle detection and proximity sensing
7	Goniometers	Joints	Measure the angular displacement of joints
8	Foot-Pressure Sensors	Shoes/Footplates	Measure the distribution of pressure on the user's feet during walking
9	Environmental Sensors	Frames	Provide data about the user's surroundings. Example are: temperature and humidity sensors
10	Load Cells	Actuators/Frames	Measure the applied load or force at specific points
11	Inertial Measurement Units (IMUs)	Frames/Joints	Measure the orientation, angular velocity, and linear acceleration of body segments and joints. Example are: accelerometers and gyroscopes
12	Biometric Sensors	Frames	Gather physiological data to assess the user's physical state and adjust the exoskeleton's assistance accordingly. Examples are: heart rate monitors, skin temperature sensors, or perspiration sensors

5. ACADEMIC PUBLICATIONS

In this phase, a search for relevant information is conducted in an array of databases, scholarly journals, conference proceedings, among other accredited sources. The main objective is to gather relevant studies across these source for a state-of-the-art analysis, thereby identifying the current ideas, challenges and future opportunities. In this case, documents are selected based on predefined inclusion and exclusion criteria. For excluding documents: upper limb exoskeletons, soft exo-suits, unpowered exoskeletons and documents in languages other than English language are all eliminated. Therefore, the academic publications search process in this phase involves the following steps: *Database Selection, Keywords Selection, String Construction, Document Collection, Bibliometric Analysis, Critical Analysis and Gaps Identification*.

5.1 Database Selection

In this step, there is the need to select accredited scientific databases relevant to the field of investigation for documents search. Although, there are many databases available for documents search, the choice of number and type of database to be selected depend on the objectivity of the researcher. For this work specifically, since the aim and objective is to investigate the state-of-the-art, challenges and opportunities in control strategies for lower limb exoskeletons, four (4) accredited research databases are selected: *Scopus, Web of Science, PubMed and IEEE Xplore*.

5.2 Keyword Selection

Selecting appropriate keywords for documents search determines the quality and relevancy of the search results. The selection is done through a careful identification of key concepts from the defined and formulated problem. Considering the case study, two important key concepts are identified (Control Strategy and Lower Limb Exoskeletons). However, from these concepts, alternative keywords were also associated. Therefore, for control strategy: sEMG-Based control, EEG-based control are selected and for Lower Limb Exoskeleton: Exoskeletons and Lower Limb Extremity are selected.

5.3 String Construction

In this step, strings are constructed and are used for documents search. For some databases, a special technique are applied for string construction in order to maximize relevant result extraction. In this case, "?" is used to search for alternative spellings for a word (colo?r will capture both spellings of the word colour/color), "#" is used to replace a definite but variable character (organi#ation will capture spelling with a z or s), abbreviations (LLE for Lower Limb Exoskeletons). and "*" at the end of a word searches for variant endings (exoskeleto* will find exoskeleton, exoskeletons etc).

Moreover, similar concepts are combined using "OR" (Control Strategy OR EEG-Based Control) and different concepts are combined using "AND" (Control Strategy AND Exoskeleton). Therefore, the following two strings are constructed.

String (1): "Control Strateg*" AND "Exoskeleton* "

String (2): ("Control Strateg*" OR "EEG-Based Control" OR "EMG-Based Control") AND ("Lower Limb Exoskeleton*" OR "Lower Limb Extremit*")

5.4 Documents Collection

In this step, the search process is conducted using the constructed strings and documents are collected from the selected databases. Table 3 presents the results for documents search using *String (1)* and *String (2)* respectively. In this case, *String (1)* aim at exploratory search that explore all control strategies related to exoskeletons including upper and lower limb exoskeleton and *String (2)* aims at secondary search that eliminate the lower limb projects. Furthermore, in the secondary analysis, Tab.4 and Tab. 5 present the top 5 documents sorted by relevance, while Tab. 6 and Tab. 7 present the top 5 documents sorted by citations from the *Web of Science* and *Scopus* respectively.

Table 3. Search Results for String(1) and String(2) for the Selected Databases

Database	Search	String(1)			String(2)		
		Result	1° Pub.	Latest Pub.	Result	1° Pub.	Latest Pub.
Web of Science	All Fields	805	2004 (1)	2024 (1)	172	2010 (1)	2023 (16)
Scopus	Ti_Ab_Key	888	1988 (1)	2024 (2)	204	2009 (1)	2023 (21)
PubMed	All Fields	157	2007 (1)	2023 (21)	32	2015 (1)	2023 (8)
IEEE Xpolre	All Fields	384	1997 (1)	2024 (1)	92	2013 (2)	2023 (5)

Table 4. Documents from *Web of Science* Database Sorted by Relevance

S/N	Document Title	1° Author	Citation
1	Review on Control Strategies for Lower Limb Rehabilitation Exoskeletons	Li <i>et al.</i> (2021a)	14
2	Hierarchical Classification of Subject-Cooperative Control Strategies for Lower Limb Exoskeletons in Gait Rehabilitation: A Systematic Review	Narayan <i>et al.</i> (2023)	0
3	Learning-based Walking Assistance Control Strategy for a Lower Limb Exoskeleton with Hemiplegia Patients	Huang <i>et al.</i> (2018)	18
4	Robotic orthoses for gait rehabilitation: An overview of mechanical design and control strategies	Jamwal <i>et al.</i> (2020)	15
5	A Novel Balance Control Strategy Based on Enhanced Stability Pyramid Index and Dynamic Movement Primitives for a Lower Limb Human-Exoskeleton System	Xu <i>et al.</i> (2021)	15

Table 5. Documents from *Scopus* Database Sorted by Relevance

S/N	Document Title	Author	Citation
1	A Review on Hybrid FES-Robotic Control Strategies of Lower-Limb Exoskeleton Robots for Gait Rehabilitation	Lin <i>et al.</i> (2022)	0
2	Single-Layer Learning-Based Predictive Control with Echo State Network for Pneumatic-Muscle-Actuators-Driven Exoskeleton	Cao <i>et al.</i> (2021)	15
3	Hierarchical Classification of Subject-Cooperative Control Strategies for Lower Limb Exoskeletons in Gait Rehabilitation: A Systematic Review	Narayan <i>et al.</i> (2023)	0
4	Command Filter Backstepping Sliding Model Control for Lower-Limb Exoskeleton	Yang <i>et al.</i> (2017)	15
5	Review on Control Strategies for Lower Limb Rehabilitation Exoskeletons	Li <i>et al.</i> (2021a)	21

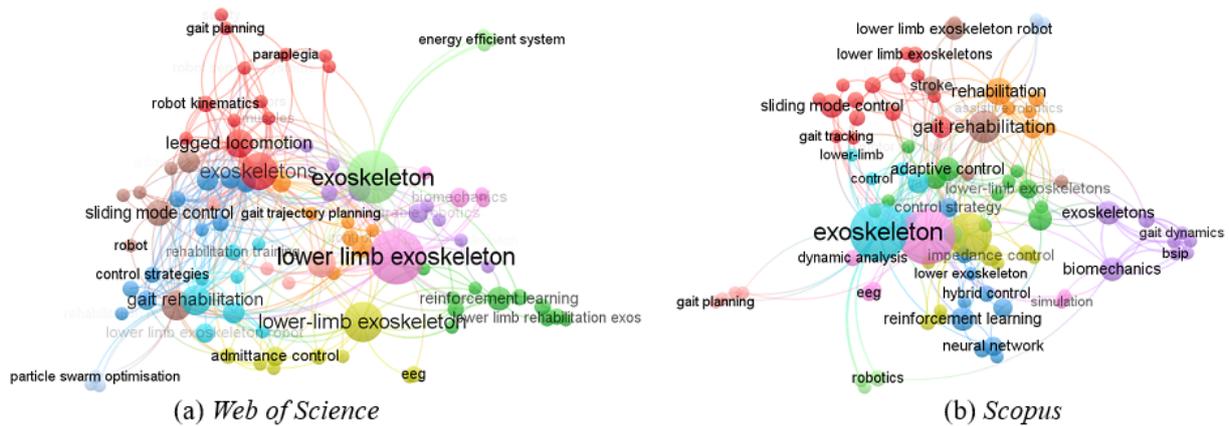


Figure 4. Author Keywords Co-occurrence Analysis using using VOSviewer: (a) *Web of Science* and (b) *Scopus*

5.6 Critical Analysis

After analysing various commercial products and academic publications on control strategies for lower limb exoskeletons, the general framework for these control strategies was identified to follow this trajectory: The user’s data is obtained by three possible methods (Human intent, Biological Signals or Joints Angles) → Which is sent to User-Machine Interface for control commands extraction → The control commands are then sent to the controller for appropriate actions on the exoskeleton system → The user receives feedback for close loop control strategy to be complete, see Fig. 5.

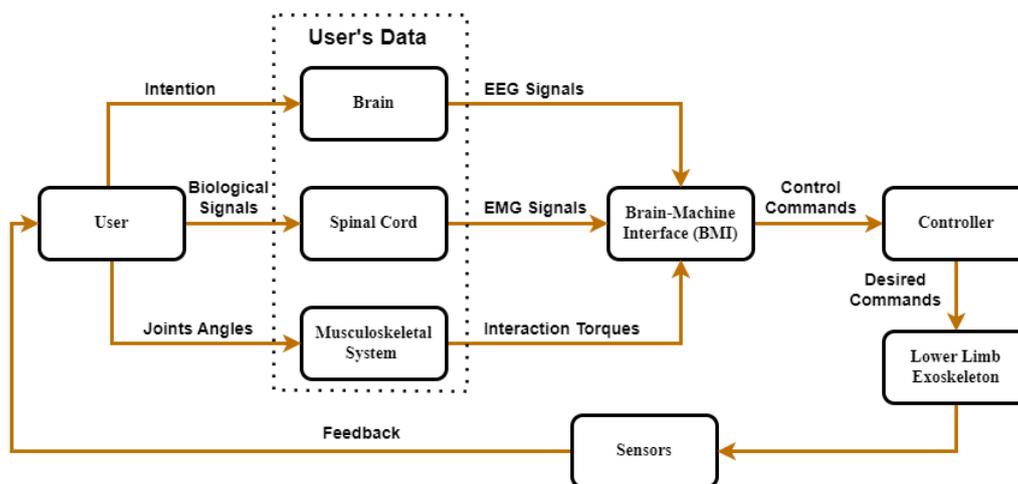


Figure 5. General Framework Observed for Control Strategies in Lower Limb Exoskeletons

One of the most recent and relevant publications found in the literature is Li *et al.* (2021a) titled "review on control strategies for lower limb rehabilitation exoskeletons". In this review, the state-of-the-art in control strategies for lower limb exoskeletons is clearly discussed and categorized into eight classes based on their similarities. Among this classifications are: Trajectory Tracking, Admittance Shaping, Controller Utilizing Backdrivability, Virtual Constraint, Oscillator-Based Control, sEMG-Based Control, EEG-Based Control, and Control of Hybrid Exoskeleton. Moreover, the three major challenges currently facing the implementation of these strategies, which include the three "Hows": (1) How to detect human intention, (2) How to do motion control with given intentions, and (3) How to optimize control parameters to suit different individuals are also discussed. Therefore, this reference is highly recommended when it comes to understanding control strategies applied to rehabilitation lower limb exoskeletons.

Apart from the classifications made by Li *et al.* (2021a), other projects presented control strategies in different perspectives. In Xia *et al.* (2020), a bio-signal enhanced adaptive impedance controller is presented. In this approach, the main focus is to determine the human lower extremity dynamics through a neural network-based torque estimation method with surface electromyogram signals (sEMG), by employing the radial basis function neural network (RBF NN) enhanced adaptive impedance controller to ensure exoskeleton track desired motion trajectory of a human operator. Other works that use the impedance approach include Huo *et al.* (2022), Sacchini *et al.* (2022). In Li *et al.* (2018b), a hybrid phase control based on fuzzy gain sliding mode controller is presented. Other work that use fuzzy approach include Kunyou and Lumin (2021).

In general, various control strategies were presented by different authors, some of the main keywords observed are: A trajectory tracking approach Sharifi *et al.* (2022), plantar pressure approach Peng *et al.* (2021), EMG-based control Chen *et al.* (2015), Hybrid FES-exoskeleton control Dunkelberger *et al.* (2023), fuzzy method Li *et al.* (2018b), adaptive event-triggered motion tracking control Peng *et al.* (2021), adaptive sliding mode control with sEMG Li *et al.* (2018a), real-time locomotion mode recognition and assistive torque control Liu and Wang (2020), sliding model impulsive control, robust adaptive back-stepping, adaptive neural network strategy Zhang *et al.* (2020) and Hao *et al.* (2020), Human-in-the-Loop Control Strategy Wei *et al.* (2021) and Li *et al.* (2021b), among others.

5.7 Gaps Identification

In this step, a careful identification of gaps in the literature is performed. This is done through a critical analysis of the available projects in the literature. For this work specifically, some gaps identified from the state-of-the-art analysis are as follows: (1) There is the need for better, more precise and robust decoding algorithms for human intention and biological signals when designing EEG-based and sEMG-based controllers. (2) There is the need for more intelligent control algorithms that will boost the human-robot interaction, (3) There is also a lacuna in human-exoskeleton interaction with uncertain dynamical parameters. (4) Design and development of predictive control systems. (5) Designing the control strategies on embedded systems.

6. CONCLUSION

This paper proposed a review methodology for scientific investigations, and applied it to investigate control strategies for lower limb exoskeletons. The methodology was able to capture the state-of-the-art control strategies across different sources, identifying the lacuna in their design and implementation. The methodology showed robustness in performance, hence can serve as a dependable framework for organizing and synthesizing the extensive corpus of literature on this and other research topics, guaranteeing the reliability and impartiality of the investigation process.

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