Advances in Robotic Rehabilitation for Lower Limb Recovery and Walking Assistance

Avances en rehabilitación robótica para la recuperación de miembros inferiores y asistencia al caminar

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Abstract

Introduction: Rehabilitation engineering for human gait is a rapidly growing field that automates therapeutic interventions, reducing the physical effort required from therapists. This enables therapists to concentrate on implementing clinical protocols for physical rehabilitation and motor re-learning. The assisted robotic rehabilitation systems also enable the assessment of motor recovery by measuring key parameters such as force patterns, interaction dynamics, and angular movements.
Objective: The study seeks to provide a comprehensive descriptive review of robotic platforms developed for the rehabilitation and assistance of human gait.
Methods: Given the rapid advancements in exoskeleton technology, particular emphasis was placed on incorporating the most recent studies. However, due to the topic's complexity, a broader research timeframe, spanning the last 14 years, was also considered. The review followed a comprehensive search strategy across multiple databases, including ScienceDirect, Springer Nature, IEEE/ASME, Frontiers, Elsevier, Taylor & Francis, Google Scholar, MDPI, Scopus, ResearchGate, Sage, MDPI y John Wiley & Sons, aiming to identify all relevant technologies related to lower limb exoskeletons.
Results: Rehabilitation and assistance robotics is a multidisciplinary field, covering areas such as biomechanics, human-machine interaction, control strategies, actuator design, and sensor integration. This study contributes a classification table that summarizes the most representative rehabilitation robotic platforms, highlighting their features and differences using comparative variables.
Conclusion: The descriptive analysis shows that overground gait trainers are the most advanced and widely used systems in rehabilitation robotics, emphasizing their effectiveness in meeting the complex needs of gait rehabilitation, making them a critical focus for future research.

Keywords: Assisted rehabilitation, Assisted robotic rehabilitation system, Extremity lower exoskeletons, Lower limb exoskeletons, Robot-based assisted rehabilitation, Robotic rehabilitation system, Walking assistants, Wearable robots.

Resumen

Introducción: La ingeniería de rehabilitación para la marcha humana es un campo de rápido crecimiento que automatiza las intervenciones terapéuticas, reduciendo el esfuerzo físico requerido de los terapeutas. Esto permite que los terapeutas se concentren en aplicar los protocolos clínicos para el entrenamiento físico y el re-aprendizaje motor. Los sistemas de rehabilitación robótica asistida también permiten la evaluación de la recuperación motora mediante la medición de parámetros clave como los patrones de fuerza, la dinámica de interacción y los movimientos angulares.
Objetivo: El estudio busca ofrecer una revisión descriptiva integral de las plataformas robóticas desarrolladas para la rehabilitación y asistencia de la marcha humana.
Métodos: Dado el rápido avance de la tecnología de exoesqueletos, se hizo un énfasis particular en incorporar los estudios más recientes. Sin embargo, debido a la complejidad del tema, también se consideró un marco temporal de investigación más amplio, abarcando los últimos 14 años. La revisión siguió una estrategia de búsqueda integral en múltiples bases de datos, incluyendo ScienceDirect, Springer Nature, IEEE/ASME, Frontiers, Elsevier, Taylor & Francis, Google Scholar, MDPI, Scopus, ResearchGate, Sage, MDPI y John Wiley & Sons, con el objetivo de identificar todas las tecnologías relevantes relacionadas con los exoesqueletos de miembros inferiores.
Resultados: La robótica de rehabilitación y asistencia es un campo multidisciplinario que abarca áreas como la biomecánica, la interacción humano-máquina, las estrategias de control, el diseño de actuadores y la integración de sensores. Este estudio contribuye con una tabla de clasificación que resume las plataformas robóticas de rehabilitación más representativas, destacando sus características y diferencias mediante variables comparativas.
Conclusión: El análisis descriptivo muestra que los entrenadores de marcha sobre terreno son los sistemas más avanzados y ampliamente utilizados en la robótica de rehabilitación, destacando su efectividad para abordar las complejas necesidades de la rehabilitación de la marcha, lo que los convierte en un foco crítico para la investigación futura.

Palabras clave: Rehabilitación asistida, Sistema de rehabilitación robótica asistida, Exoesqueletos de extremidades inferiores, Exoesqueletos de miembros inferiores, Rehabilitación asistida basada en robots, Sistema de rehabilitación robótica, Asistentes para caminar, Robots usables.

Contribution to the literature

Why was it done?
This study was conducted to provide a structured and comprehensive review of robotic platforms designed for lower limb rehabilitation and walking assistance. Given the multidisciplinary nature of rehabilitation robotics, the research aimed to classify and analyze existing systems based on their rehabilitation principles, highlighting their key features, technological advancements, and challenges in clinical application.

What were the most relevant results?
The study identified overground gait trainers as the most advanced and widely used robotic rehabilitation systems, emphasizing their ability to replicate natural movement patterns and improve patient outcomes. Additionally, the classification of robotic platforms provided a comparative analysis of key design and control features, demonstrating the interplay between biomechanics, human-machine interaction, and control strategies in shaping rehabilitation effectiveness.

What do these results provide?
These findings offer valuable insights into the current state and future direction of robotic rehabilitation systems. By identifying key technological trends and challenges—such as the need for adaptive control strategies and personalized rehabilitation—this study contributes to the optimization of robotic-assisted therapy. The results serve as a reference for researchers and developers, supporting the advancement of more effective, user-centered rehabilitation technologies.
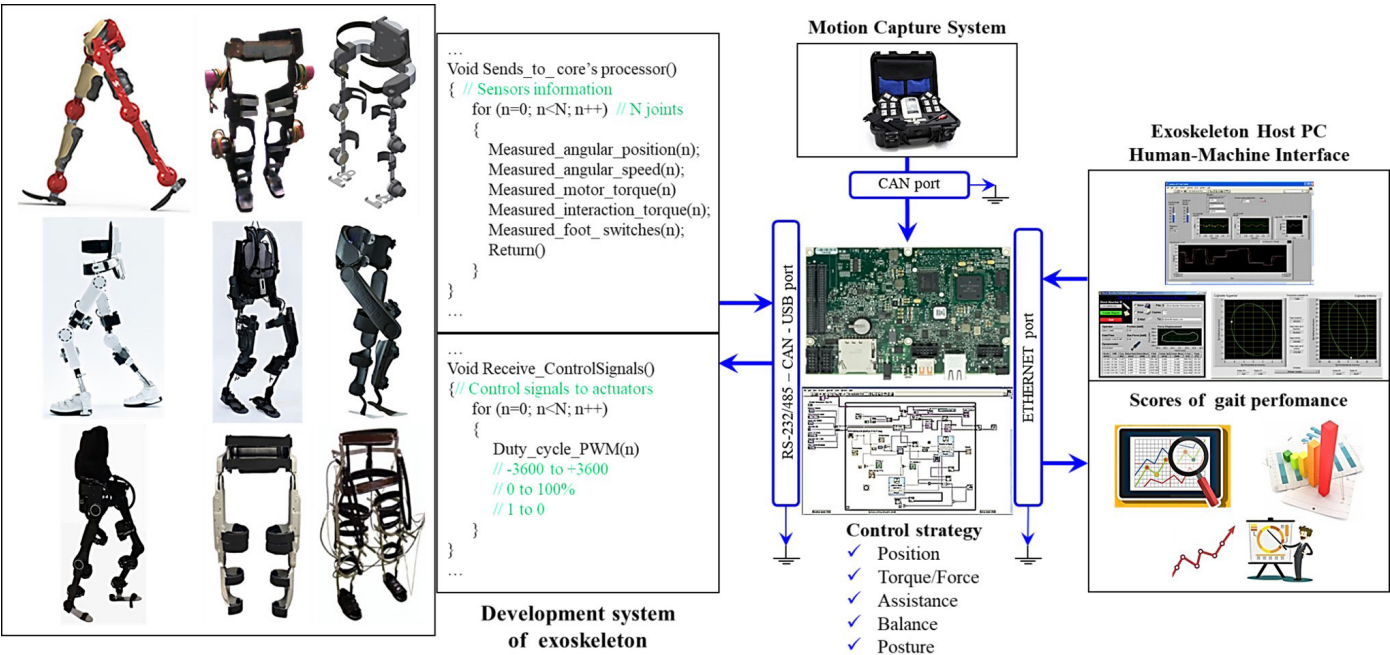
Introduction

Rehabilitation engineering in the context of human gait is an emerging and rapidly growing field, offering innovative solutions to automate therapeutic interventions. Robotic rehabilitation reduces the physical effort required from therapists without replacing their direct involvement. This enables therapists to focus on implementing clinical protocols for physical training or motor re-learning with more intensive and coordinated repetitive movements. These systems can alleviate joint pressure through Body Weight Support (BWS) mechanisms generating suitable physiological gait patterns tailored to the anthropometry of patient, and facilitating passive/active participation of patient through human-robot interaction. Additionally, these systems allow for quantitative assessment of functional motor restoration through the analysis of force patterns, interaction dynamics, angular movements, and other relevant parameters. In the mid-term, the integration of this technology by rehabilitation centers could significantly reduce the economic cost of therapies, making them more accessible to vulnerable populations with disabilities and thereby enhancing their quality of life.

This paper presents a comprehensive review of state-of-the-art advancements in robotic-assisted rehabilitation systems, with an emphasis on lower limb recovery and walking support. The second section outlines the methodology used to classify robotic platforms for the rehabilitation and assistance of individuals with motor disabilities, including treadmill-based walking assistants, footplate-based walking assistants, mobile walking assistants, and stationary walking assistants. The third section provides a detailed analysis of the results. The fourth section discusses the results, while the fifth section summarizes the main conclusions.

Methods

The authors of this study conducted an extensive scoping review of the existing literature to identify areas of interest and refine the objectives and scope of their analysis. This initial exploration provided a foundation for defining the aim of the review and ensuring a focused approach.

Considering the rapid advancements in exoskeleton technology in recent years, particular emphasis was placed on incorporating the most recent studies. However, recognizing the importance and complexity of the topic, a broader research timeframe was deemed necessary, encompassing papers published over the past 14 years.

The methodological framework for this review involved a comprehensive search across multiple databases and sources, including ScienceDirect, Springer Nature, IEEE/ASME, Frontiers, Elsevier, Taylor & Francis, Google Scholar, MDPI, Scopus, ResearchGate, Sage, MDPI y John Wiley & Sons. This process aimed to identify all relevant technologies related to lower limb exoskeletons.

The primary keywords used during the initial search were "Lower limb exoskeletons," "Extremity lower exoskeletons," and "Lower limb robotic exoskeletons." To refine the search and handle the substantial volume of available information, additional filtering keywords were applied, including terms such as "Wearable robots," "Assistance," "Rehabilitation," "Assistive," "Assistive robotic device," "Assistive robotic system," "Robotic rehabilitation system," "Assisted robotic rehabilitation system," "Robotic rehabilitation," "Assisted rehabilitation," "Robot-based assisted rehabilitation,"

"Robot-assisted lower limb rehabilitation," "Walking assistants," "Assisted gait," and "Assisted gait rehabilitation."

This approach yielded the identification of numerous candidate papers for further analysis. Each paper was meticulously analyzed to extract information on technologies applied to lower limb exoskeletons, spanning diverse fields such as Rehabilitation Engineering, Robotics, Control Systems, Automation, Biomechanics, Human-Machine Systems, Medical Devices, Mechatronics Engineering, Mechanical Engineering, and Industrial Medicine.

The selection of articles for this state-of-the-art review was guided by well-defined inclusion criteria to guarantee a comprehensive and high-quality analysis of the selected literature. Firstly, thematic relevance was prioritized, ensuring that all selected studies directly address the research topic and its key subthemes. Secondly, emphasis was placed on scientific rigor and quality, including articles published in indexed journals, subjected to peer review, and employing robust methodologies. Thirdly, the recency of publications was considered, favoring recent studies to reflect the latest advancements while incorporating seminal works fundamental to understanding the field's historical development. Fourthly, originality and contribution were essential, focusing on research that provides significant findings, novel perspectives, or emerging methodologies. Fifthly, geographic and cultural diversity was encouraged to achieve a global perspective, with attention to studies from specific regions when relevant. Sixthly, reliable sources and citation impact were considered, selecting articles from reputable journals with significant academic influence. Lastly, the inclusion encompassed various publication types, such as original research articles, systematic reviews, surveys, book chapters, patents, conference proceedings, meta-analyses, and technical reports, depending on their relevance and contribution to the topic. These criteria collectively ensure a comprehensive, balanced, and critical synthesis of the literature.

The present comprehensive review of state-of-the-art developments is not primarily intended to be innovative in itself; however, it stands out by offering an original perspective that enables a systematic and comprehensive categorization and interpretation of existing advancements in the field. Furthermore, it identifies emerging trends that highlight potentially underexplored or unrecognized areas, which are crucial for guiding future research. In this regard, the work presented makes a significant contribution to the development of the field by providing an exhaustive review based on the main studies, trends, technologies, and relevant theories, carefully compiled from reliable sources, and by enhancing the global understanding of the subject under consideration.

Robotic systems for gait rehabilitation

The development of robotic assistants through different disciplines and biomedical research is allowing the coupling and human-robot synchronization in a feasible system, where the robot can support the human in a specific task. The coupled system is based on the human contributing intelligence and then benefiting from the performance, power and precision of the robotic system; which generates a user-oriented robot. In (1) advancement of mechanisms and controllers for robotic-assisted rehabilitation are discussed. In addition, the study (2) presents a classification of Lower Extremity Exoskeletons (LEE) into three distinct categories based on their applications and intended users: gait rehabilitation, assistance with human locomotion, and augmentation of human strength.

Robotic systems designed to assist in the rehabilitation of human gait are often referred to as platforms or robotic assistants and are categorized based on their underlying rehabilitation principles, Figure 1: treadmill assistants, footplate-based assistants, mobile assistants, and stationary assistants.
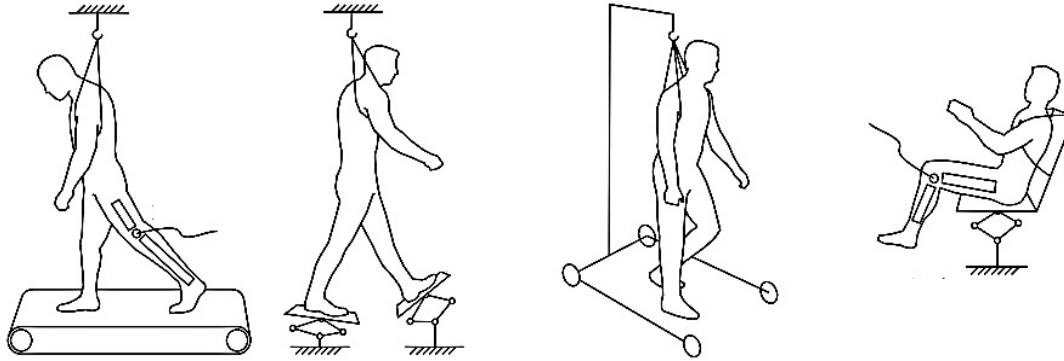

Figure 1. Robotic assistants for assisted gait rehabilitation. (a) Exoskeleton with treadmill, (b) Foot plates, (c) Autonomous exoskeleton and (d) Stationary. (3)

Walking assistants with treadmill

Traditional rehabilitation therapies are based on a clinical protocol that includes the use of a treadmill combined with a partial body-weight support (BWS) system as part of the process to address functional mobility. For example, the patient's limbs and hips are assisted by three therapists to facilitate walking on the treadmill, while a harness assists in supporting the body weight. The primary aim of robotic systems is to automate and refine this conventional approach, thereby reducing the physical effort required from therapists (4). These systems achieve this by employing motorized joints to assist the patient's lower limbs, adjusting weight distribution, and incorporating biofeedback to promote active patient participation.

Typically, these systems contain an exoskeleton and a treadmill, Figure 1(a). On the market there is the Lokomat, the LokoHelp, the ReoAmbulator, and the Walkbot. The Lokomat, developed by Hocoma AG, is composed of a robotic gait orthosis with BWS and treadmill (5,9,10); it has servomotors for the hip and knee joints, Figure 2(a); the speed of the treadmill is synchronized with the gait speed of the orthosis. The LokoHelp, designed by the LokoHelp Group, is an electromechanical device created to enhance gait recovery following brain injury (11); it is placed on the treadmill and secured with a clamp, it also incorporates a system to support the patient's body weight, Figure 2(b). The ReoAmbulator, developed by Motorika Ltd. and distributed in the United States under the name AutoAmbulator, represents an additional robotic system incorporating BWS and a treadmill (7,12); the robotic arms are attached to the patient's legs specifically at the thigh and ankle, they move in a step-by-step pattern, Figure 2(c). The Walkbot owned by P&S Mechanics Figure 2 (d), is a robot-assisted gait training rehabilitation system that provides a natural and accurate gait pattern for the patient, and uses a hip/knee/ankle joint drive motor in the sagittal plane combined with a BWS system and a motorized treadmill (8,13); the Walkbot series has four models: the Walkbot_G which is compatible for adults and pediatric patients with neurological or musculoskeletal impairments, Figure 2 (d1); the Walkbot_S, which offers a smart interactive training

mode and uses real-time biofeedback to keep patients motivated, Figure 2 (d2); the Walkbot_K, which is dedicated to pediatric patients, Figure 2 (d3); and the Walk_P which is a rehabilitation medical device for adults with neurological or musculoskeletal impairments who want to perfect
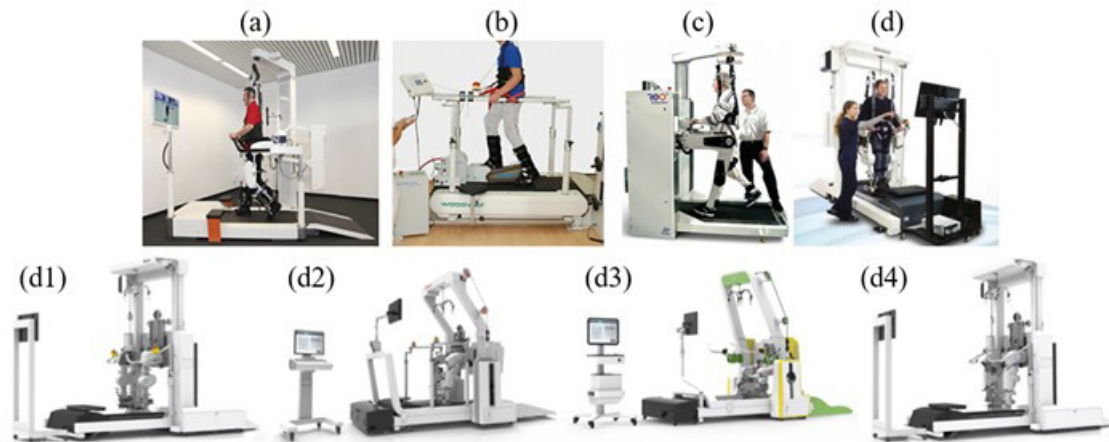

Figure 2. Walking assistants with treadmill. (a) Lokomat (5), (b) LokoHelp or Pedago (6), (c) ReoAmbulator (7), (d) Walkbot (8). Walkbot series: (d1) Global (Walkbot_G), (d2) Superior (Walkbot_S), (d3) KID (Walkbot_K), and (d4) Premium (Walkbot_P).

Similarly, there are research platforms focused on assisted gait rehabilitation, such as the RUVEM platform, Figure 3, which is a laboratory device used to develop research work within the GICI group at Universidad del Valle (15) and is dedicated on supporting the rehabilitation of people with neuromotor impairments; it consists of a lower extremity exoskeleton, an instrumented treadmill, and a BWS system (14,16–19); the exoskeleton can reproduce a physiological gait pattern and achieve a large deviation balance; the treadmill is a commercial system modified for gait rehabilitation at a maximum speed of 0.8 m/s, it can provide a constant speed during therapy and was modified to aid in walking safety through side rails along the belt and has a positioning control that automatically adjusts the band speed based on the individual's velocity; the BWS system compensates a percentage of weight supported by the lower limbs of patients with reduced mobility; RUVEM is under development, and the purpose is the active tracking of the vertical movement of the subject's trunk guaranteeing a natural gait on the treadmill. The Biomechatronics Laboratory at the University of California has designed and developed multiple robotic devices intended for gait training in individuals recovering from spinal cord injuries; these include the Ambulation-assisting Robotic Tool for Human Rehabilitation (ARTHuR) (20), which is designed to measure and adjust steps on a treadmill; the Pneumatically Operated Gait Orthosis (POGO), an enhanced version of the Leg-Robot; and the Pelvic Assist Manipulator (PAM) (21), which facilitates natural pelvic movement control.

Figure 3. Assisted rehabilitation platform for human gait, RUVEM (14)

Other robotic assistants such as the Active Leg Exoskeleton (ALEX) with linear actuators in the hip and knee joints; it has a force controller to aid the patient through the Assist-As-Needed (AAN) approach (22). The LOwer-extremity Powered ExoSkeleton (LOPES) is a robot for gait assisted-rehabilitation; it facilitates the movement of an individual's legs during treadmill walking and it is flexibly connected at the level of the pelvis. (23). The actuated compliant robotic orthosis used for automated locomotion training called ALTRACO, is a step rehabilitation robot equipped with a lightweight pneumatic actuator (24); the robotic orthosis is composed of a unilateral exoskeleton and a support arm to stabilize through gravitational balance. The Robotic Gait Rehabilitation (RGR) system targets secondary deviations in walking for patients who have experienced a cerebrovascular accident; while the patient is undergoing treadmill training, vertical forces are applied to the pelvis, exerting forces to counteract deviations from typical pelvic motion (25); the device is attached to the patient using an orthopedic support system. The String-Man assistant, created by Fraunhofer IPK in Berlin, is a robotic platform aimed at facilitating gait rehabilitation and promoting the recovery of motor functions; its design includes a kinematic structure composed of seven cables connected to the patient's torso (26).

Walking assistants based on foot plates

Certain systems for assisted gait rehabilitation utilize programmable footplates as a foundational component, Figure 1(b); in these systems, the patient's feet rest on separate plates, and the robotic mechanism controls their movements to simulate gait patterns and ground reaction forces. The subject is standing and is supported by parallel bars and a harness; the movement is transmitted from the soles of the feet to the joints; however, these systems are heavyweight.

The following assistants are based on foot plates: The Gangtrainer (GT I), Figure 4(a), marketed by Reha-Stim, assists in the restoration of lower limb mobility by subtracting the weight of the patient and adapting the gait speed based on the patient's individual capacity (27); the patient is positioned on two plates and secured with a harness, and the movements generated by the system can simulate the support and swing phase; the assistant is equipped with cables attached to the patient, which control the vertical and lateral adjustments of the center of mass. The gait rehabilitation system known as GaitMaster5 (GM5), developed at the University of Tsukuba, involves

securing the patient's feet to platforms equipped with sensors (28), as shown in Figure 4(b); these bases move the user's feet forward, replicating walking motions or simulating activities such as climbing stairs. The HapticWalker is a haptic locomotion interface able of simulating slow and smooth trajectories, such as walking on flat ground or going up/down stairs, also, it simulates movements such as walking on uneven ground, even tripping or slipping, which requires a system with higher-order dynamics (30); it is a re-design of the GT I system based on footplates with fully programmable trajectories, Figure 4(c).
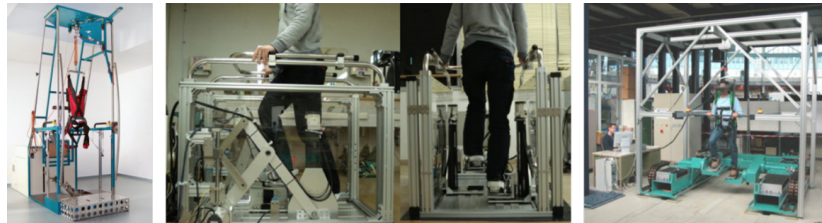

Figure 4. Walking assistants based on foot plates. (a) Gangtrainer GT I (27), (b) GaitMaster5 (28) and (c) HapticWalker (29).

Other footplate-based platforms, such as the Lower-Limb Rehabilitation Robot (LLRR), it aids patients in replicating natural walking movements and exercising the muscles of the legs (31); it consists of a control system for the posture of the steps and weight reduction. A robot with six-degree-of-freedom designed for gait rehabilitation was developed at Gyeongsang National University (32); this system features connections to the upper and lower limbs, enabling adjustments to gait speed across different terrains; it comprises an upper limb device, a sliding mechanism, two plantar bases, and a BWS system.

Mobile walking assistants

These robotic systems generate ground-level gait by enabling patients to transfer and move autonomously, rather than relying on predefined movement patterns, Figure 1(c). This type of assistant is known as an autonomous exoskeleton and has the purpose of assisting autonomous gait; the exoskeleton is lightweight and its power source is a battery.

Among these types of assistants are the following: The KineAssist developed by Kinea Design, LLC, is a robotic system designed for gait and balance rehabilitation (33); it is equipped with a torso and pelvic harness linked to a mobile robotic platform, as shown in Figure 5(a); the robot operates based on the forces exerted by the patient that are measured using load cells integrated into the pelvic harness. The robotic rehabilitation walker known as WalkTrainer from Swortec SA, consists of a pelvic orthosis, BWS, a bilateral orthosis and an electro-stimulator operated in real time (34,40); it is a walker for gait re-education, Figure 5(b). The ReWalk from Argo Medical Technologies Ltd., is a motorized, quasi-robotic and wearable suit, Figure 5(c), that can be used in therapeutic activities (35); this suit is equipped with direct current motors at the joints, batteries, sensors, and a control system deployed in a computer; the movements of the upper body are sensed and used to initiate and maintain the gait process. The wearable robot called Hybrid Assistive Limb (HAL)

is designed for diverse purposes, such as rehabilitation and heavy-duty support; it is offered in multiple several setups, including full-body and a two-leg versions (41); furthermore, a single-leg version of the HAL has been created to aid the gait of individuals with hemiplegia, as illustrated in Figure 5(d). The ABLE Exoskeleton is a device to assist subjects with mobility limitations that affect the ability to stand, walk, and sit., Figure 5(e); the clinicians are able to modify the level of support offered at each joint (37). The legX is an exoskeleton designed to support the user's knees, enabling them to perform squats repeatedly or sustain them for extended periods with minimal effort (38); additionally, the exoskeleton functions as an adjustable chair, capable of being set to various heights., Figure 5(f). The PhoeniX exoskeleton is a lower-body-powered hip orthosis designed to aid people with mobility impairments, Figure 5(g); it is being developed by SuitX, formerly US Bionics; it has two actuators in the hips; for the swing phase, the knee joints allow support during stance and ground clearance, (39). Other assistants such as WHERE I and II are also mobile systems for gait rehabilitation that allow training on the ground (42).
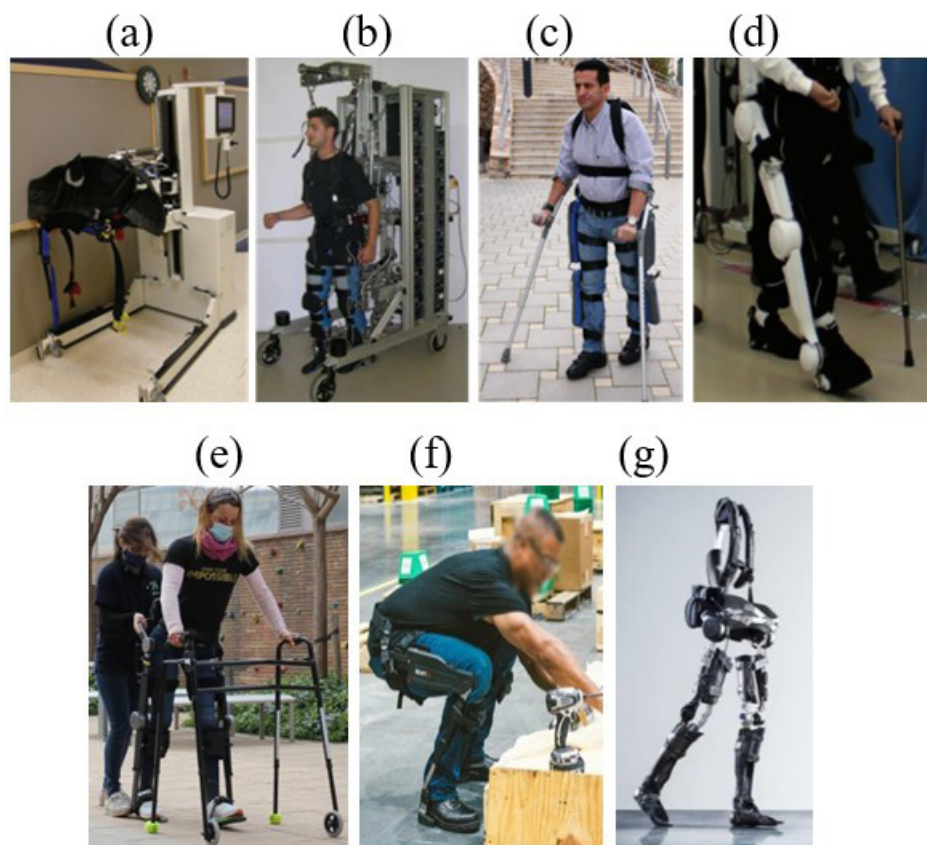

Figure 5. Mobile walking assistants. (a) KineAssist (33), (b) WalkTrainer (34), (c) ReWalk (35), (d). HAL Single-leg (36), (e) Able (37), (f) lefX (38), and (g) PhoeniX (39).

A commercial over-ground rehabilitation system designed for research is the Exo-H3 lower limb robotic exoskeleton owned by Technaid S.L. (43), which can assist people with partial loss of the ability to walk after a stroke; it is a powered hip-knee-ankle exoskeleton with six actuated joints in

the sagittal plane; the mechanical system comprises servomotors, gears, extension bars, insoles, hips attachment, and straps, Figure 6; the mainframe is composed of stainless steel and high resistance aluminum; the exoskeleton adapts to different sizes.

Figure 6. Exo-H3 lower limb exoskeleton (43).

In reference (44), a catalog is presented that classifies exoskeletons by category (commercial, industrial, medical, and military) and by application (assistive, augmentation, pediatric, rehabilitation, research, etc.). This report on exoskeletons emphasizes providing updates and resources related to the emerging field of exoskeletons, exosuits, and wearable robotics technology. Also, the systematic review (45) provides an overview of the key technical features of 25 wearable lower-limb exoskeletons, including factors such as commercial availability, supported joints, target population, control methods, power storage, gait phase detection, initiation of gait, intended use (rehabilitation/augmentation), certification (CE mark/FDA approval), and the intended user group, among others. Similarly, the paper (46) explores the history of robotic exoskeletons designed for bipedal walking, discussing the challenges present in current biped exoskeleton designs; it further categorizes these exoskeletons into three main focuses: medical, industrial, and military, while also emphasizing the differences in the prominence of their scope of use within existing designs.

Stationary walking assistants

The aim of these assistants is to promote muscle strengthening, develop fatigue resistance, and support the range of motion and gait physiological pattern, Figure 1(d); also, the robotic system is aimed at patients without the ability to stand and who need to exercise and activate the circulatory, renal, and locomotor system.

Robotic systems developed based on this principle include the MotionMaker, created by the Swortec SA company (47); this system is designed for static training, as illustrated in Figure 7(a), allowing physical conditioning with the active participation of non-functional limbs, which are secured to the orthosis at the foot level to naturally replicate ground reaction forces; additionally,

it incorporates controlled electrical stimulation adjusted to the patient's exertion levels. The rehabilitation robot known as Lambda, is a device for rehabilitation and physical conditioning in ankle rotation and lower limbs movement in the sagittal-plane (48), Figure 7(b). A rehabilitation system for the lower extremities developed by the National Institute of Advanced Industrial Science and Technology (AIST) in Tsukuba., Figure 7(c), it has multiple degrees of freedom, and it uses a wire-driven mechanism (49).
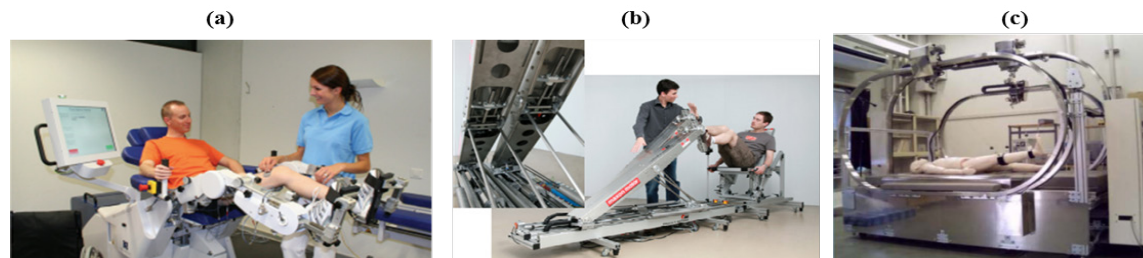

Figure 7. Stationary walking assistants. (a) MotionMaker (47), (b) Lambda (48), and (c) Wire-driven mechanism (49).

Results

This study introduces a systematically developed classification table of the most representative robotic platforms for gait rehabilitation and assistance (see Supplementary File: Table 1). The classification process spanned approximately two years and was included in the González-Mejía's doctoral dissertation (14).

Supplementary file: Table 1.

Data availability: The information generated and analyzed during this study is available in the Open Science Framework repository - https://osf.io/6q43s

File format: pdf.

Title: Rehabilitation robotic platforms. Robotic systems for the assisted rehabilitation of human gait can be called platforms or robotic assistants, which are grouped according to the principle of rehabilitation: Treadmill assistants, footplate-based assistants, mobile assistants, and stationary assistants.

Description: The classification table is based on a carefully selected set of comparison variables, aiming to provide a structured and detailed analysis of the key features of each platform, such as:

Robotic systems for gait rehabilitation: Treadmill gait trainers, Foot-plate-based gait trainers, Overground gait trainers, and Stationary gait trainers.

Robotic rehabilitation device

Company

Degree of freedom (DoF): Actuated (A), Passive (P or Un-actuated), and Rigid (R)

Hip DoF: Flexion/Extension, Abduction/Adduction, and External rotation/Internal rotation

Knee DoF: Flexion/Extension

Ankle DoF: Plantar flexion/Dorsiflexion, Inversion/Eversion, Abduction/Adduction, and

*Pronation/**Supination
*Pronation: All three planes, applied motion based on a combination of: Eversion, abduction and dorsiflexion.
**Supination: All three planes, applied motion based on a combination of: Inversion, adduction and plantar-flexion.

Actuation

Body Weight Support (BWS): cable Body Weight Support (cBWS), and structural Body Weight Support (sBWS).

Sensors

Control strategies

Step trajectory

Device weight: Engineering units, $[Kg]$.

Clinical trials

Status: Research stage (R), Commercially available (C), Clinical usage (Cu), Military (M), and Abandoned (there is no ongoing work more than four years - A). Within the table above, you will find references (50-108)

Discussion

Although this paper does not discuss how the features of robotic rehabilitation platforms for gait influence rehabilitation effectiveness, their relevance and supporting evidence are undeniable. The design and control characteristics of these platforms significantly impact their therapeutic outcomes and the user experience, as highlighted in the literature. For instance, the design approach presented in "Design Approaches of an Exoskeleton for Human Neuromotor Rehabilitation" (109) demonstrates the importance of mimicking natural human gait patterns to support neuromotor recovery; by utilizing the recorded motions of healthy individuals, this exoskeleton design aims to replicate a complete gait cycle, thereby promoting walking recovery for patients with neuromotor disorders. Complementarily, the review conducted in "Control strategies used in lower limb exoskeletons for gait rehabilitation after brain injury" (110) underscores the critical role of control strategies in maximizing clinical outcomes; this work highlights how advancements in robotic controllers over the past decade have facilitated better interaction between exoskeletons and brain-injured patients, although the optimal strategies for stimulating motor function recovery remain under investigation. Together, these studies illustrate the interplay between mechanical design and control methodologies in shaping both the therapeutic impact and the user-centered

experience of robotic rehabilitation systems, emphasizing the need for further integration of these elements to align with clinical evidence and user-specific needs. Additionally, the classification table (Supplementary file: Table 1) references articles that present the results of clinical trials conducted on the studied platforms.

The descriptive analysis highlights that overground gait trainers are currently the most advanced and widely employed systems in the field of rehabilitation robotics. This widespread use reflects their capability to address the multifaceted challenges inherent in gait rehabilitation, particularly in restoring natural movement patterns in individuals with impaired mobility. These systems offer significant advantages by enabling rehabilitation in a more functional, real-world environment, which is crucial for improving patient outcomes. Their role in the rehabilitation process underscores their importance as a central area of focus for ongoing research and technological development. Continued advancements in overground gait trainers may lead to more personalized, effective therapies, enhancing their potential to accommodate the varying needs of patients with different types of gait impairments. Further exploration of their design, control strategies, and integration with other rehabilitation technologies could optimize their clinical application and broaden their effectiveness in diverse rehabilitation settings.

The need for adaptive and personalized rehabilitation robots highlights a critical intersection between biomechanics, control engineering, and artificial intelligence. One of the primary challenges in achieving dynamic adaptability lies in developing robust control algorithms that can process real-time biomechanical feedback while maintaining stability and safety. Machine learning and predictive modeling could play a crucial role in refining these control strategies, enabling the system to anticipate user movements and disturbances rather than merely reacting to them. Moreover, integrating multimodal sensing technologies—such as electromyography (EMG) and inertial measurement units (IMUs)—could enhance the robot's ability to assess neuromuscular responses and adapt accordingly. However, these advancements raise additional concerns, including computational efficiency, sensor reliability, and the need for extensive clinical validation to ensure efficacy across diverse patient populations. Addressing these challenges will require interdisciplinary collaboration among engineers, clinicians, and neuroscientists to develop rehabilitation robots that are not only technically sophisticated but also clinically effective and accessible for widespread use.

Conclusions

This paper provides a comprehensive overview of the research background to enhance readers' knowledge and understanding of robotic systems for assisted human gait rehabilitation. A classification of these systems is presented, categorized based on rehabilitation principles, including treadmill-based assistants, footplate-based assistants, mobile assistants, and stationary assistants. The review adopts a descriptive approach to highlight key characteristics within these categories.

The field of rehabilitation and assistance robotics is highly multidisciplinary, encompassing areas such as biomechanics, human-machine interaction, control strategies, actuator design, and sensor integration. As a significant contribution, this study offers a classification table summarizing the most representative rehabilitation robotic platforms. This table highlights their distinctive features

and differences using comparative variables, providing a valuable reference for researchers and developers in the field.

In conclusion, while current rehabilitation robots have demonstrated significant progress in assisting with gait recovery, they still face considerable challenges in personalizing their physical characteristics to meet the specific needs of individual users. The variability in patients' conditions and the diversity in motor impairments require robots that can adjust dynamically to provide tailored support. Furthermore, robotic systems must be designed to accommodate the unpredictable disturbances induced by the user, which can occur during therapy sessions and interfere with the effectiveness of the rehabilitation process. To overcome these obstacles, the development of advanced control strategies becomes essential. These strategies must ensure seamless and adaptive interactions, allowing the robot to continuously adjust its support based on real-time feedback from the user. By integrating such adaptive systems, future rehabilitation robots could enhance user comfort, safety, and overall therapeutic outcomes, ultimately improving the quality of gait recovery for individuals with mobility impairments.

Author contributions

Sergey González-Mejía: Research, Methodology, Funding acquisition, Conceptualization, Writing – original draft, Writing – review & editing. José M. Ramírez-Scarpetta: Methodology, Funding acquisition, Project management, Writing – review & editing.

Funding

Conflicts of interest

The authors declare that they have no competing interests.

Ethical implications

Not applicable

Acknowledgments

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