Vol 27 (1)

Ingeniería y Competitividad
Vol 27 (1) 2025 doi: 10.25100/iyc.v27i1.14594

ISSN
0123-3033
e- 2027-8284

Review Article

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

Sergey González-Mejía[1] José M. Ramírez-Scarpetta[1]

[1]Industrial Control Research Group (GICI), Electrical and Electronic Engineering School, Universidad del Valle, Cali, Colombia.

How to cite?

González-Mejía, S., Ramírez-Scarpetta, J.M., Advances in Robotic Rehabilitation for Lower Limb Recovery and Walking Assistance Ingeniería y Competitividad, 2025, 27(1) e-30314594

https://doi.org/10.25100/iyc.v27i1.14594

Recibido: 21-11-24
Evaluado: 20-12-24
Aceptado: 14-02-25
Online: 25-02-25

Correspondence

sergey.gonzalez@correounivalle.edu.co

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.

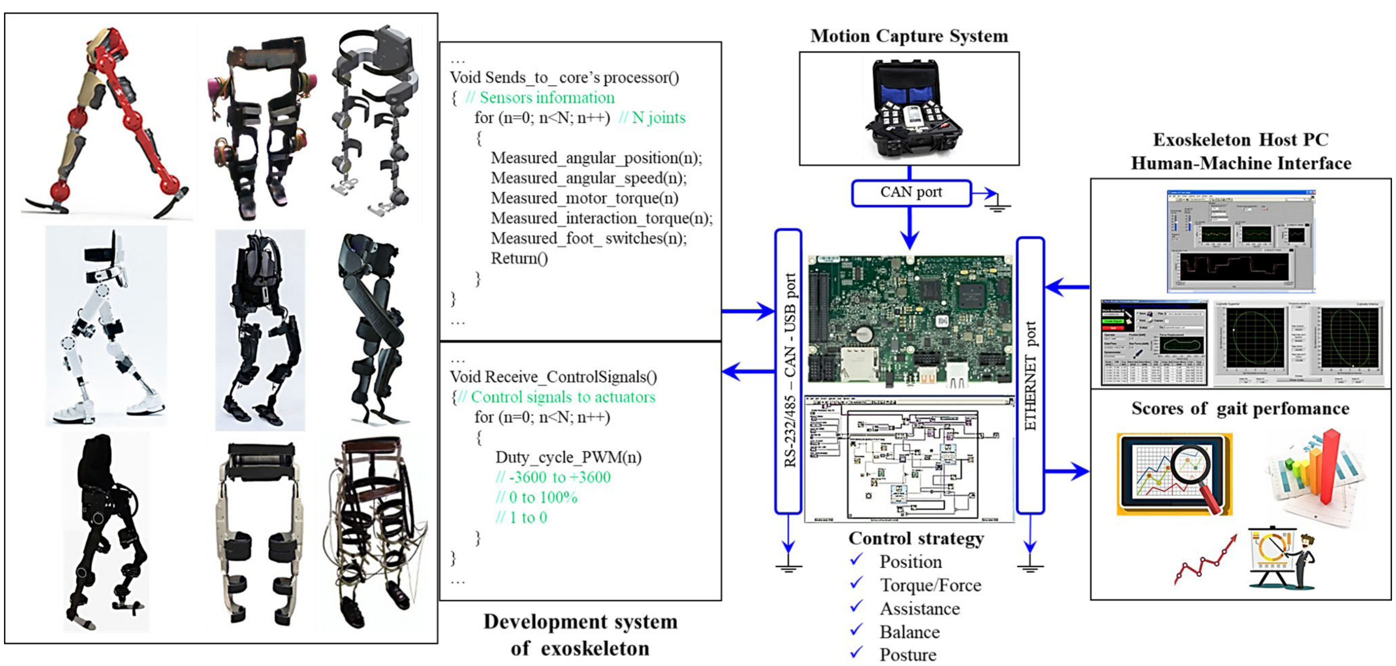
Palabras clave: Rehabilitación asistida, Sistema de rehabilitación robótica asistida, Exoesqueletos de extremidades inferiores, Exoesqueletos de miembros inferiores, Rehabilitación asistida basada en robots, Sistema de rehabilitación robótica, Asistentes para caminar, Robots usables.

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.



doi: 10.25100/iyc.v27i1.14594

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,”

doi: 10.25100/iyc.v27i1.14594

"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.

doi: 10.25100/iyc.v27i1.14594

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.

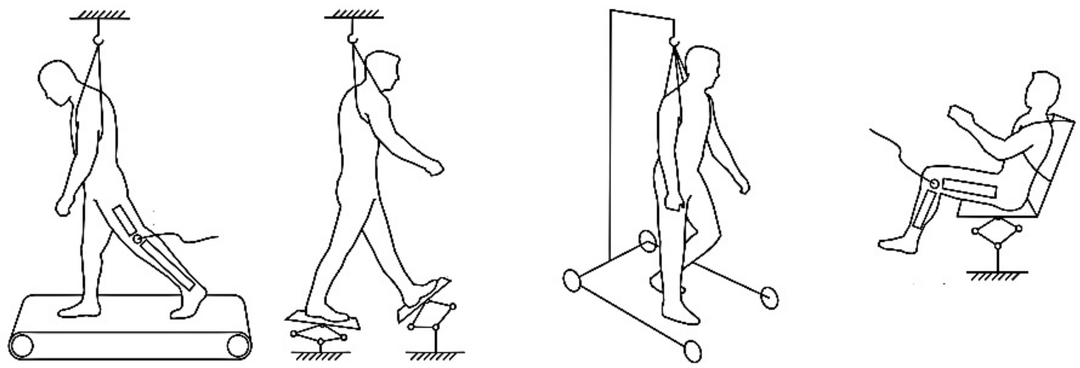


Figure 1. Robotic assistants for assisted gait rehabilitation. (a) Exoskeleton with treadmill, (b) Foot plates, (c) Autonomous exoskeleton and (d) Stationary. (3)

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

doi: 10.25100/iyc.v27i1.14594

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

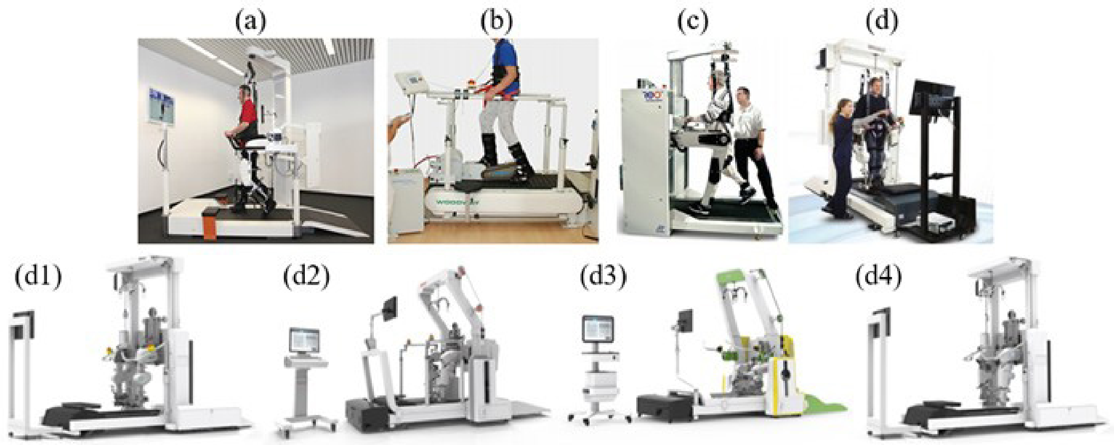


Figure 2. Walking assistants with treadmill. (a) Lokomat (5), (b) LokoHelp or Pedago (6), (c) ReoAmbulator (7), (d) Walkbot (8). Walkbot series: (d1) Global (Walkbot_G), (d2) Superior (Walkbot_S), (d3) KID (Walkbot_K), and (d4) Premium (Walkbot_P).

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.

doi: 10.25100/iyc.v27i1.14594

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

doi: 10.25100/iyc.v27i1.14594

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).

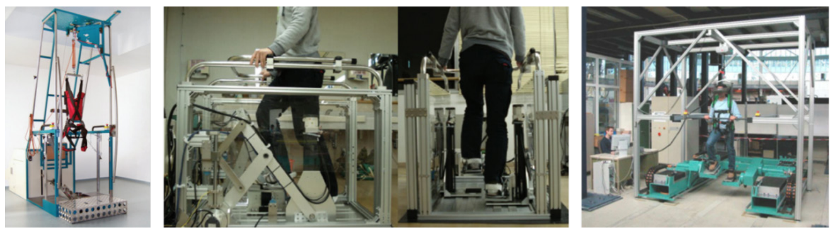


Figure 4. Walking assistants based on foot plates. (a) Gangtrainer GT I (27), (b) GaitMaster5 (28) and (c) HapticWalker (29).

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)

doi: 10.25100/iyc.v27i1.14594

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).

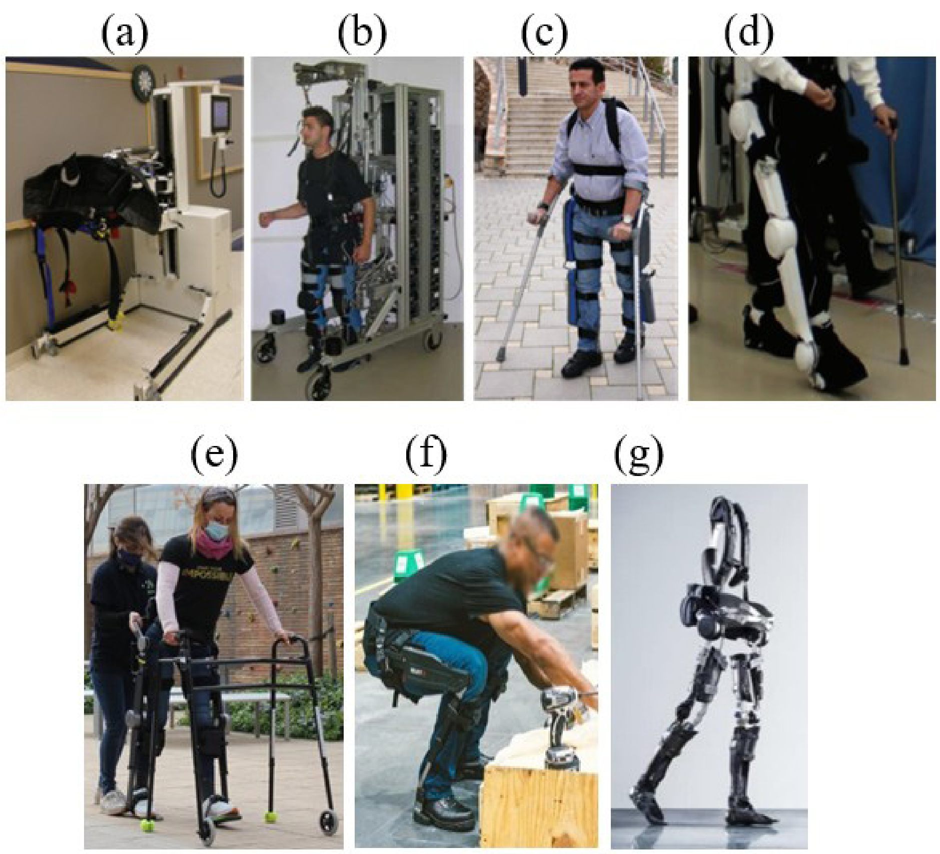


Figure 5. Mobile walking assistants. (a) KineAssist (33), (b) WalkTrainer (34), (c) ReWalk (35), (d). HAL Single-leg (36), (e) Able (37), (f) lefX (38), and (g) PhoeniX (39).

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

doi: 10.25100/iyc.v27i1.14594

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,

doi: 10.25100/iyc.v27i1.14594

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).

(a) (b) (c)

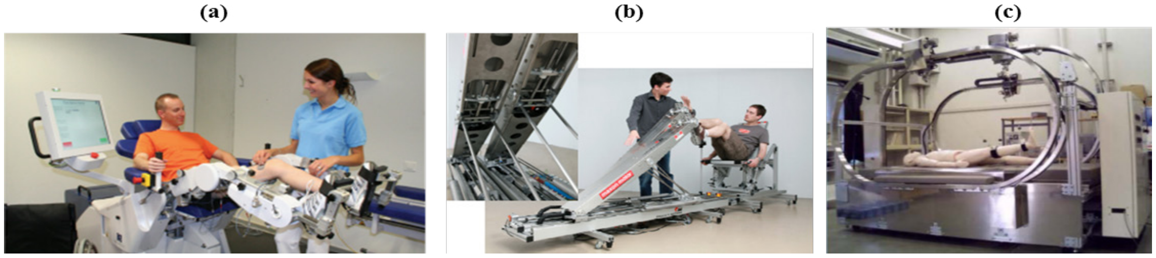


Figure 7. Stationary walking assistants. (a) MotionMaker (47), (b) Lambda (48), and (c) Wire-driven mechanism (49).

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

doi: 10.25100/iyc.v27i1.14594

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).

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

doi: 10.25100/iyc.v27i1.14594

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

doi: 10.25100/iyc.v27i1.14594

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

This publication received funding from Universidad del Valle under the project entitled "Plataforma tecnológica modular para la valoración objetiva de la marcha humana" with C.I. code 21259.

Conflicts of interest

The authors declare that they have no competing interests.

Ethical implications

Not applicable

Acknowledgments

The authors appreciate the funding support provided by Universidad del Valle and the Ministry of Science, Technology, and Innovation (Minciencias – Open call 647).

References

1. Meng W, Liu Q, Zhou Z, Ai Q, Sheng B, Xie SS. Recent development of mechanisms and control strategies for robot-assisted lower limb rehabilitation. Mechatronics [Internet]. 2015 Oct;31:132–45. Available from: http://dx.doi.org/10.1016/j.mechatronics.2015.04.005
2. Chen B, Ma H, Qin LY, Gao F, Chan KM, Law SW, et al. Recent developments and challenges of lower extremity exoskeletons. J Orthop Transl [Internet]. 2016 Apr;5:26–37. Available from: http://linkinghub.elsevier.com/retrieve/pii/S2214031X15000716

3. Díaz I, Gil JJ, Sánchez E. Lower-Limb Robotic Rehabilitation: Literature Review and Challenges. Vol. 2011, Journal of Robotics. 2011. p. 1–11.

4. Galvez J, Reinkensmeyer D. Robotics for Gait Training After Spinal Cord Injury. Top Spinal Cord Inj Rehabil [Internet]. 2005 Oct;11(2):18–33. Available from: http://archive.scijournal.com/doi/abs/10.1310/DAMJ-G43A-16EH-1BDK

5. Colombo G, Joerg M, Schreier R, Dietz V. Treadmill training of paraplegic patients using a robotic orthosis. J Rehabil Res Dev [Internet]. 2000;37(6):693–700. Available from: http://www.ncbi.nlm.nih.gov/pubmed/11321005

6. Freivogel S, Mehrholz J, Husak-Sotomayor T, Schmalohr D. Gait training with the newly developed 'LokoHelp'-system is feasible for non-ambulatory patients after stroke, spinal cord and brain injury. A feasibility study. Brain Inj [Internet]. 2008 Jan;22(7–8):625–32. Available from: http://www.tandfonline.com/doi/full/10.1080/02699050801941771

7. West RG. Powered gait orthosis and method of utilizing same [Internet]. Vol. 1, US Patent US006689075B2. United States; 2006. Available from: https://patents.google.com/patent/US6689075B2/en

8. P&S Mechanics Co. Ltd. WALKBOT Exoskeleton gait training robot [Internet]. 2024 [cited 2024 Aug 1]. Available from: https://www.walkbot.co.kr/en/sub/product-introduction.php

9. Wyss D, Vallery H, Hocoma AG. Gait Rehabilitation Robot (Lokomat). Zurich, Switzerland: ETH Zurich; 2012 [cited 2015 Sep 30]. Sensory-Motor Systems Lab. Available from: https://sms.hest.ethz.ch/research/past-research-projects/lower-limb-exoskeletons-and-exosuits/lokomat-gait-rehabilitation-robot.html

10. Marchal-Crespo L, Riener R. Technology of the Robotic Gait Orthosis Lokomat. In: Reinkensmeyer DJ, Marchal-Crespo L, Dietz V, editors. Neurorehabilitation Technology [Internet]. Cham: Springer International Publishing; 2022. p. 665–81. Available from: https://doi.org/10.1007/978-3-031-08995-4_29

11. Freivogel S, Mehrholz J, Husak-Sotomayor T, Schmalohr D. Gait training with the newly developed 'LokoHelp'-system is feasible for non-ambulatory patients after stroke, spinal cord and brain injury. A feasibility study. Brain Inj. 2008;22(7–8):625–32.

12. Motorika. ReoAmbulator Robotic Gait Training Device [Internet]. 2012 [cited 2015 Sep 30]. Available from: https://exoskeletonreport.com/product/reoambulator/#google_vignette

13. Olmos-Gómez R, Calvo-Muñoz I, Gómez-Conesa A. Treatment with robot-assisted gait trainer Walkbot along with physiotherapy vs. isolated physiotherapy in children and adolescents with cerebral palsy. Experimental study. BMC Neurol [Internet]. 2024 Jul 15;24(1):245. Available from: https://bmcneurol.biomedcentral.com/articles/10.1186/s12883-024-03750-9

14. González-Mejía S. Partial Assistance Control on a Robotic Platform with an Exoskeleton for the Human Gait Rehabilitation [Internet]. Doctoral thesis, Universidad del Valle; 2023. Available from: https://doi.org/10.17605/OSF.IO/J7XFH

doi: 10.25100/iyc.v27i1.14594

15. GICI. Industrial Control Research Group - Universidad del Valle [Internet]. 2022 [cited 2022 Aug 14]. Available from: https://gici.univalle.edu.co/

16. González-Mejía S, Ramírez JM. Gait Assisted Rehabilitation Platform – RUVEM. In: IX Congreso Iberoamericano de Tecnologías de Apoyo a la Discapacidad Iberdiscap [Internet]. Bogotá DC.; 2017. p. 1–8. Available from: https://reasiste.umh.es/portfolio/iberdiscap-2017/

17. Echeverri EM, González-Mejía S, Ramírez JM, Rosero E. Plataforma de rehabilitación asistida para marcha - RUVEM: Integración de los subsistemas de soporte. In: X Congreso Iberoamericano de Tecnologías de Apoyo a la Discapacidad Iberdiscap [Internet]. Buenos Aires, Argentina; 2019. Available from: https://reasiste.umh.es/portfolio/iberdiscap-2019/

18. Loaiza A, Rosero E, Ramírez JM. Active body weight support system for lower limb rehabilitation. In: VIII Jornadas AITADIS de Tecnologías de Apoyo a la Discapacidad [Internet]. México; 2018. Available from: https://www.aitadis.org/wp/934-2/

19. Loaiza AE, Garcia JI, Buitrago JT. Development of a Body Weight Support System Employing Model-Based System Engineering Methodology. Technologies [Internet]. 2024 Jul 23;12(8):118. Available from: https://www.mdpi.com/2227-7080/12/8/118

20. Reinkensmeyer D, Wynne JH, Harkema SJ. A robotic tool for studying locomotor adaptation and rehabilitation. Proc Second Jt 24th Annu Conf Annu Fall Meet Biomed Eng Soc [Engineering Med Biol. 2002;3:2353–4.

21. Reinkensmeyer DJ, Aoyagi D, Emken JL, Galvez J a, Ichinose W, Kerdanyan G, et al. Tools for understanding and optimizing robotic gait training. J Rehabil Res Dev. 2006;43(5):657–70.

22. Banala SK, Agrawal SK, Scholz JP. Active Leg Exoskeleton (ALEX) for gait rehabilitation of motor-impaired patients. 2007 IEEE 10th Int Conf Rehabil Robot ICORR'07. 2007;00(c):401–7.

23. Veneman JF, Kruidhof R, Hekman EEG, Ekkelenkamp R, Van Asseldonk EHF, Van Der Kooij H. Design and evaluation of the LOPES exoskeleton robot for interactive gait rehabilitation. IEEE Trans Neural Syst Rehabil Eng. 2007;15(1):379–86.

24. Beyl P, Van Damme M, Van Ham R, Versluys R, Vanderborght B, Lefeber D. An exoskeleton for gait rehabilitation: Prototype design and control principle. Proc - IEEE Int Conf Robot Autom. 2008;2037–42.

25. Pietrusinski M, Cajigas I, Mizikacioglu Y, Goldsmith M, Bonato P, Mavroidis C. Gait rehabilitation therapy using robot generated force fields applied at the pelvis. 2010 IEEE Haptics Symp HAPTICS 2010. 2010;401–7.

26. Surdilovic D, Bernhardt R. STRING-MAN: a new wire robot for gait rehabilitation. IEEE Int Conf Robot Autom 2004 Proceedings ICRA '04 2004. 2004;2:2031–6.

27. Hesse S, Uhlenbrock D. A mechanized gait trainer for restoration of gait. J Rehabil Res Dev [Internet]. 2000;37(6):701–8. Available from: https://pubmed.ncbi.nlm.nih.gov/11321006/

28. Yano H, Tamefusa S, Tanaka N, Saitou H, Iwata H. Gait rehabilitation system for stair climbing and descending. In: 2010 IEEE Haptics Symposium [Internet]. IEEE; 2010. p. 393–400. Available from: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=5444627

doi: 10.25100/iyc.v27i1.14594

29. Schmidt H, Hesse S, Bernhardt R, Krüger J. HapticWalker a novel haptic foot device. ACM Trans Appl Percept [Internet]. 2005 Apr 1;2(2):166-80 https://doi.org/10.1109/HAPTIC.2010.5444627.

30. Schmidt H. HapticWalker - A novel haptic device for walking simulation. In: Proceedings of the EuroHaptics Conference [Internet]. Munich, Germany; 2004. p. 60–7. Available from: http://portal.acm.org/citation.cfm?doid=1060581.1060589

31. Chen S, Wang Y, Li S, Wang G, Huang Y, Mao X. Lower limb rehabilitation robot. In: 2009 ASME/IFToMM International Conference on Reconfigurable Mechanisms and Robots [Internet]. London: IEEE; 2009. p. 439–43. Available from: https://ieeexplore.ieee.org/document/5173866

32. Yoon J, Novandy B, Yoon CH, Park KJ. A 6-DOF gait rehabilitation robot with upper and lower limb connections that allows walking velocity updates on various terrains. IEEE/ASME Trans Mechatronics. 2010;15(2):201–15.

33. Peshkin M, Brown D a., Santos-Munné JJ, Makhlin A, Lewis E, Colgate JE, et al. KineAssist: A robotic overground gait and balance training device. Proc 2005 IEEE 9th Int Conf Rehabil Robot. 2005;2005:241–6.

34. Bouri M, Stauffer Y, Schmitt C, Allemand Y, Gnemmi S, Clavel R, et al. The WalkTrainer™: A Robotic system for walking rehabilitation. 2006 IEEE Int Conf Robot Biomimetics, ROBIO 2006. 2006;1616–21.

35. Goffer A. Gait-locomotor apparatus [Internet]. Google Patents; US7153242, 2006. Available from: http://www.google.com/patents/US7153242

36. Kawamoto H, Suwoong Lee, Kanbe S, Sankai Y. Power assist method for HAL-3 using EMG-based feedback controller. In: SMC'03 Conference Proceedings 2003 IEEE International Conference on Systems, Man and Cybernetics Conference Theme - System Security and Assurance (Cat No03CH37483) [Internet]. IEEE; 2003. p. 1648–53. Available from: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=1244649

37. ABLE Human Motion S.L. ABLE Human Motion Exoskeleton | Backed by leading clinical institutions [Internet]. 2022 [cited 2022 Jul 26]. Available from: https://www.ablehumanmotion.com/able-human-motion-exoskeleton/

38. Pillai M V., Van Engelhoven L, Kazerooni H. Evaluation of a Lower Leg Support Exoskeleton on Floor and Below Hip Height Panel Work. Hum Factors J Hum Factors Ergon Soc [Internet]. 2020 May 9;62(3):489–500. Available from: http://journals.sagepub.com/doi/10.1177/0018720820907752

39. SuitX. Phoenix | suitX [Internet]. 2017 [cited 2022 Jul 26]. Available from: https://www.suitx.com/phoenix-medical-exoskeleton

40. Allemand Y, Stauffer Y, Clavel R, Brodard R. Design of a new lower extremity orthosis for overground gait training with the WalkTrainer. In: 2009 IEEE International Conference on Rehabilitation Robotics [Internet]. IEEE; 2009. p. 550–5. Available from: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=5209585

doi: 10.25100/iyc.v27i1.14594

41. Kawamoto H, Sankai Y. Power Assist System HAL-3 for Gait Disorder Person. Comput Help people with Spec needs [Internet]. 2002;196–203. Available from: https://www.researchgate.net/profile/Anne-Marie-Burn-2/publication/221009609_TeDUB_A_System_for_Presenting_and_Exploring_Technical_Drawings_for_Blind_People/links/5b8e5c9b45851540d1c50da4/TeDUB-A-System-for-Presenting-and-Exploring-Technical-Drawings-for-Blind-People.pdf#page=219

42. Seo KH, Lee JJ. The development of two mobile gait rehabilitation systems. IEEE Trans Neural Syst Rehabil Eng. 2009;17(2):156–66.

43. Technaid S.L. Robotic Exoskeleton Exo-H3 [Internet]. 2021 [cited 2022 Aug 16]. Available from: https://www.technaid.com/products/robotic-exoskeleton-exo-exoesqueleto-h3/

44. Exoskeleton Report LLC. Exoskeleton Catalog Archives - Exoskeleton Report [Internet]. 2021 [cited 2022 Jul 26]. Available from: https://exoskeletonreport.com/product-category/exoskeleton-catalog/

45. Rodríguez-Fernández A, Lobo-Prat J, Font-Llagunes JM. Systematic review on wearable lower-limb exoskeletons for gait training in neuromuscular impairments. J Neuroeng Rehabil [Internet]. 2021 Dec 1;18(1):22. Available from: https://doi.org/10.1186/s12984-021-00815-5

46. Tijjani I, Kumar S, Boukheddimi M. A Survey on Design and Control of Lower Extremity Exoskeletons for Bipedal Walking. Appl Sci [Internet]. 2022 Feb 25;12(5):2395. Available from: https://www.mdpi.com/2076-3417/12/5/2395

47. Schmitt C, Métrailler P, Al-Khodairy A, Brodard R, Fournier J, Bouri M, et al. The MotionMaker: a Rehabilitation System Combining an Orthosis With Closed Loop Electrical Muscle Stimulation. In: 8 Vienna International Workshop on Functional Electrical Stimulation [Internet]. 2004. p. 117–20. Available from: https://infoscience.epfl.ch/entities/publication/2a6ab0ca-0013-4bbb-a3bd-55d11fb5418b/statistics

48. Bouri M, Le Gall B, Clavel R. A new concept of parallel robot for rehabilitation and fitness: The Lambda. 2009 IEEE Int Conf Robot Biomimetics, ROBIO 2009. 2009;2503–8.

49. Homma K, Fukuda O, Sugawara J, Nagata Y, Usuba M. A wire-driven leg rehabilitation system: development of a 4-DOF experimental system. In: Advanced Intelligent Mechatronics, 2003 AIM 2003 Proceedings 2003 IEEE/ASME International Conference on [Internet]. 2003. p. 908–13. Available from: http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=1225463%5Cn10.1109/AIM.2003.1225463%5CnA wire-driven leg rehabilitation system-development of a 4-DOF experimental system (2).pdf

50. Colombo G, Wirz M, Dietz V. Driven gait orthosis for improvement of locomotor training in paraplegic patients. Spinal Cord [Internet]. 2001 May;39(5):252–5. Available from: http://www.nature.com/doifinder/10.1038/sj.sc.3101154

51. Wirz M, Zemon DH, Rupp R, Scheel A, Colombo G, Dietz V, et al. Effectiveness of automated locomotor training in patients with chronic incomplete spinal cord injury: A multicenter trial. Arch Phys Med Rehabil. 2005;86(4):672–80.

doi: 10.25100/iyc.v27i1.14594

52. Hornby TG, Zemon DH, Campbell D. Robotic-assisted, body-weight-supported treadmill training in individuals following motor incomplete spinal cord injury. Phys Ther. 2005;85(1):52–66.

53. Hidler J, Nichols D, Pelliccio M, Brady K, Campbell DD, Kahn JH, et al. Multicenter randomized clinical trial evaluating the effectiveness of the Lokomat in subacute stroke. Neurorehabil Neural Repair. 2009;23(1):5–13.

54. Westlake KP, Patten C. Pilot study of Lokomat versus manual-assisted treadmill training for locomotor recovery post-stroke. J Neuroeng Rehabil. 2009;6:18.

55. Mehrholz J, Pohl M. Electromechanical-Assisted Gait Training After Stroke: A Systematic Review Comparing End-Effector and Exoskeleton Devices. J Rehabil Med [Internet]. 2012;44(3):193–9. https://doi.org/10.2340/16501977-0943

56. Freivogel S, Schmalohr D, Mehrholz J. Improved walking ability and reduced therapeutic stress with an electromechanical gait device. J Rehabil Med. 2009;41(9):734–9.

57. Fisher S. Use of Autoambulator for mobility improvement in patients with central nervous system (CNS) injury or disease. In: Neurorehabilitation and neural repair. 2008. p. 556.

58. Fisher S, Lucas L, Adam Thrasher T. Robot-Assisted Gait Training for Patients with Hemiparesis Due to Stroke. Top Stroke Rehabil [Internet]. 2011 May;18(3):269–76. Available from: http://www.ncbi.nlm.nih.gov/pubmed/21642064

59. Emken JL, Wynne JH, Harkema SJ, Reinkensmeyer DJ. A robotic device for manipulating human stepping. IEEE Trans Robot [Internet]. 2006 Feb;22(1):185–9. Available from: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=1589012

60. Emken JL, Harkema SJ, Beres-Jones J a., Ferreira CK, Reinkensmeyer DJ. Feasibility of manual teach-and-replay and continuous impedance shaping for robotic locomotor training following spinal cord injury. IEEE Trans Biomed Eng. 2008;55(1):322–34.

61. Ichinose WE, Reinkensmeyer DJ, Aoyagi D, Lin JT, Ngai K, Edgerton VR, et al. A robotic device for measuring and controlling pelvic motion during locomotor rehabilitation. In: Proceedings of the 25th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (IEEE Cat No03CH37439) [Internet]. IEEE; 2003. p. 1690–3. https://doi.org/10.1109/IEMBS.2003.1279715

62. Aoyagi D, Inchinose WE, Reinkensmeyer DJ, Bobrow JE. Human Step Rehabilitation Using a Robot Attached to the Pelvis. In: Dynamic Systems and Control, Parts A and B [Internet]. ASME; 2004. p. 443–9. Available from: http://proceedings.asmedigitalcollection.asme.org/proceeding.aspx?articleid=1652235

63. Aoyagi D, Ichinose WE, Harkema SJ, Reinkensmeyer DJ, Bobrow JE. An Assistive Robotic Device That Can Synchronize to the Pelvic Motion During Human Gait Training. In: 9th International Conference on Rehabilitation Robotics, 2005 ICORR 2005 [Internet]. IEEE; 2005. p. 565–8. https://doi.org/10.1109/ICORR.2005.1502026

doi: 10.25100/iyc.v27i1.14594

64. Zanotto D, Stegall P, Agrawal SK. ALEX III: A novel robotic platform with 12 DOFs for human gait training. In: 2013 IEEE International Conference on Robotics and Automation [Internet]. IEEE; 2013. p. 3914–9. Available from: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=6631128

65. Banala SK, Kim SH, Agrawal SK, Scholz JP. Robot assisted gait training with active leg exoskeleton (ALEX). IEEE Trans Neural Syst Rehabil Eng [Internet]. 2009 Feb;17(1):2–8. Available from: http://www.ncbi.nlm.nih.gov/pubmed/19211317

66. Fleerkotte BM, Koopman B, Buurke JH, van Asseldonk EHF, van der Kooij H, Rietman JS. The effect of impedance-controlled robotic gait training on walking ability and quality in individuals with chronic incomplete spinal cord injury: an explorative study. J Neuroeng Rehabil [Internet]. 2014;11(1):26. Available from: http://www.jneuroengrehab.com/content/11/1/26

67. Asseldonk E van, Simons C, Folkersman M. Robot aided gait training according to the assist-as-needed principle in chonic stroke survivors. In: Proceedings of the Annual Meeting of the Society for Neuroscience (Poster). Chicago, Ill, USA; 2009.

68. Beyl P, Naudet J, Van Ham R, Lefeber D. Mechanical Design of an Active Knee Orthosis for Gait Rehabilitation. In: 2007 IEEE 10th International Conference on Rehabilitation Robotics [Internet]. IEEE; 2007. p. 100–5. Available from: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=4428413

69. Surdilovic D, Zhang J, Bernhardt R. STRING-MAN: Wire-robot technology for safe, flexible and human-friendly gait rehabilitation. 2007 IEEE 10th Int Conf Rehabil Robot ICORR'07. 2007;00(c):446–53.

70. Werner C, Von Frankenberg S, Treig T, Konrad M, Hesse S. Treadmill training with partial body weight support and an electromechanical gait trainer for restoration of gait in subacute stroke patients: a randomized crossover study. Stroke [Internet]. 2002 Dec;33(12):2895–901. Available from: http://www.ncbi.nlm.nih.gov/pubmed/12468788

71. Pohl M, Werner C, Holzgraefe M, Kroczek G, Mehrholz J, Wingendorf I, et al. Repetitive locomotor training and physiotherapy improve walking and basic activities of daily living after stroke: a single-blind, randomized multicentre trial (DEutsche GAngtrainerStudie, DEGAS). Clin Rehabil. 2007;21(1):17–27.

72. Peurala SH, Airaksinen O, Huuskonen P, Jäkälä P, Juhakoski M, Sandell K, et al. Effects of intensive therapy using gait trainer or floor walking exercises early after stroke. J Rehabil Med. 2009;41(3):166–73.

73. Schmidt H, Krüger J, Hesse S. HapticWalker - Haptic foot device for gait rehabilitation. In: Human Haptic Perception: Basics and Applications [Internet]. Birkhauser Verlag AG; 2008. p. 501–11. Available from: http://www.scopus.com/inward/record.url?eid=2-s2.0-84918789024&partnerID=40&md5=8d69ec54de484a78d8b3f8334f6923de

74. Hesse S, Werner C. Connecting research to the needs of patients and clinicians. Brain Res Bull. 2009;78(1):26–34.

doi: 10.25100/iyc.v27i1.14594

75. Frey M, Colombo G, Vaglio M, Bucher R, Jorg M, Riener R. A Novel Mechatronic Body Weight Support System. IEEE Trans Neural Syst Rehabil Eng [Internet]. 2006 Sep;14(3):311–21. Available from: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=1703563

76. Evolution Fitness Brasil. Eliptico Orbital Evolution Sportop E 450 [Internet]. 2013 [cited 2015 Sep 30]. Available from: https://www.youtube.com/watch?v=MLAnTb8VvM4

77. Evolution Fitness. Elíptico eletrônico evolution [Internet]. 2013 [cited 2015 Nov 24]. Available from: https://www.evolutionfitness.co/product-category/cardio/elipticas/page/2?srsltid=AfmBOood41wVx-SGYCCKz7xoDx1MSHibu3qVEjV0zx7zDGUM8NQZBbtF

78. Wang S, Wang L, Meijneke C, van Asseldonk E, Hoellinger T, Cheron G, et al. Design and Control of the MINDWALKER Exoskeleton. IEEE Trans Neural Syst Rehabil Eng [Internet]. 2015 Mar;23(2):277–86. Available from: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=6940308

79. Burgess JK, Weibel GC, Brown D a. Overground walking speed changes when subjected to body weight support conditions for nonimpaired and post stroke individuals. J Neuroeng Rehabil [Internet]. 2010;7(1):6. Available from: http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=2827418&tool=pmcentrez&rendertype=abstract

80. Allemand Y, Stauffer Y. Overground Gait Rehabilitation: First Clinical Investigation with the WalkTrainer. In: Proceedings of the European Conference on Technically Assisted Rehabilitation, (TAR ’09). Berlin, Germany; 2009.

81. Suzuki K, Kawamura Y, Hayashi T, Sakurai T, Hasegawa Y, Sankai Y. Intention-based walking support for paraplegia patient. In: Conference Proceedings - IEEE International Conference on Systems, Man and Cybernetics [Internet]. 2005. p. 2707–13. Available from: http://www.scopus.com/inward/record.url?eid=2-s2.0-27944501048&partnerID=tZOtx3y1

82. Kawamoto H, Hayashi T, Sakurai T, Eguchi K, Sankai Y. Development of single leg version of HAL for hemiplegia. Proc 31st Annu Int Conf IEEE Eng Med Biol Soc Eng Futur Biomed EMBC 2009. 2009;5038–43.

83. Strausser KA, Swift TA, Zoss AB, Kazerooni H. Prototype Medical Exoskeleton for Paraplegic Mobility: First Experimental Results. In: ASME 2010 Dynamic Systems and Control Conference, Volume 1 [Internet]. ASME; 2010. p. 453–8. Available from: http://proceedings.asmedigitalcollection.asme.org/proceeding.aspx?articleid=1613452

84. Swift TA, Strausser KA, Zoss AB, Kazerooni H. Control and Experimental Results for Post Stroke Gait Rehabilitation With a Prototype Mobile Medical Exoskeleton. In: ASME 2010 Dynamic Systems and Control Conference, Volume 1 [Internet]. ASME; 2010. p. 405–11. Available from: http://proceedings.asmedigitalcollection.asme.org/proceeding.aspx?articleid=1613434

85. Rex Bionics. Rex Bionics - Our Products [Internet]. 2015 [cited 2015 Nov 6]. Available from: https://www.rexbionics.com/product-information/

doi: 10.25100/iyc.v27i1.14594

86. Maxon motor. Robotic exoskeleton: For a better quality of life [Internet]. 2013 [cited 2015 Nov 25]. p. 1–4. Available from: http://www.maxonmotor.com/medias/sys_master/8808028438558/2013-01-en-exoskeletton.pdf?attachment=true

87. MORI Y, TANIGUCHI T, INOUE K, FUKUOKA Y, SHIROMA N. Development of a Standing Style Transfer System ABLE with Novel Crutches for a Person with Disabled Lower Limbs. J Syst Des Dyn [Internet]. 2011;5(1):83–93. Available from: http://joi.jlc.jst.go.jp/JST.JSTAGE/jsdd/5.83?from=CrossRef

88. Kong K, Moon H, Hwang B, Jeon D, Tomizuka M. Impedance compensation of SUBAR for back-drivable force-mode actuation. IEEE Trans Robot. 2009;25(3):512–21.

89. Chen F, Yu Y, Ge Y, Sun J, Deng X. WPAL for Human Power Assist during Walking Using Pseudo-compliance Control. In: 2007 International Conference on Mechatronics and Automation [Internet]. IEEE; 2007. p. 2172–6. Available from: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=4303888

90. Cao H, Ling Z, Zhu J, Wang Y, Wang W. Design frame of a leg exoskeleton for load-carrying augmentation. 2009 IEEE Int Conf Robot Biomimetics, ROBIO 2009. 2009;426–31.

91. Kiguchi K, Imada Y. EMG-based control for lower-limb power-assist exoskeletons. 2009 IEEE Work Robot Intell Informationally Struct Space, RiiSS 2009 - Proc. 2009;19–24.

92. Kwa HK, Noorden JH, Missel M, Craig T, Pratt JE, Neuhaus PD. Development of the IHMC mobility assist exoskeleton. In: Proceedings - IEEE International Conference on Robotics and Automation. 2009. p. 2556–62.

93. Hayashi Y, Kiguchi K. A lower-limb power-assist robot with perception-assist. In: Rehabilitation Robotics (ICORR), 2011 IEEE International Conference on. 2011. p. 1–6.

94. Quintero HA, Farris RJ, Goldfarb M. Control and implementation of a powered lower limb orthosis to aid walking in paraplegic individuals. In: 2011 IEEE International Conference on Rehabilitation Robotics [Internet]. IEEE; 2011. p. 1–6. Available from: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=5975481

95. Lim HB, Hoon KH, Soh YC, Tow A, Low KH. Gait planning for effective rehabilitation - From gait study to application in clinical rehabilitation. In: 2009 IEEE International Conference on Rehabilitation Robotics [Internet]. IEEE; 2009. p. 271–6. Available from: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=5209599

96. Safizadeh MR, Hussein M, Yaacob MS, Md Zain MZ, Abdullah MR, Che Kob MS, et al. Kinematic analysis of powered lower limb Orthoses for gait rehabilitation of hemiplegic and hemiparetic patients. Int J Math Model Methods Appl Sci. 2011;5(3):490–8.

97. Slavnic S, Leu A, Ristic-Durrant D, Graser A. Concept of a mobile robot-assisted gait rehabilitation system - simulation study. In: 2010 IEEE/RSJ International Conference on Intelligent Robots and Systems [Internet]. IEEE; 2010. p. 6022–7. Available from: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=5649133

doi: 10.25100/iyc.v27i1.14594

98. Saito Y, Kikuchi K, Negoto H, Oshima T, Haneyoshi T. Development of Externally Powered Lower Limb Orthosis with Bilateral-Servo Actuator. In: 9th International Conference on Rehabilitation Robotics, 2005 ICORR 2005 [Internet]. IEEE; 2005. p. 394–9. Available from: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=1501127

99. Costa N, Caldwell DG. Control of a Biomimetic "Soft-actuated" 10DoF Lower Body Exoskeleton. In: The First IEEE/RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics, 2006 BioRob 2006 [Internet]. IEEE; 2006. p. 495–501. Available from: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=1639137

100. Zabaleta H, Bureau M, Eizmendi G, Olaiz E, Medina J, Perez M. Exoskeleton design for functional rehabilitation in patients with neurological disorders and stroke. In: 2007 IEEE 10th International Conference on Rehabilitation Robotics [Internet]. IEEE; 2007. p. 112–8. Available from: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=4428415

101. Honda. Walking Assist Device with Bodyweight Support Assist [Internet]. 2009 [cited 2015 Nov 6]. Available from: https://www.honda.mx/movilidad#bodyWeight

102. Honda. Walking Assist Device with Stride Management Assist [Internet]. 2009 [cited 2015 Nov 6]. Available from: https://global.honda/en/newsroom/news/2012/c120729eng.html

103. Low KH, Yin Y. An integrated lower exoskeleton system towards design of a portable active orthotic device. Int J Robot Autom [Internet]. 2007;22(1):32–43. Available from: http://dl.acm.org/citation.cfm?id=1739807.1739811

104. Xiaopeng Liu, Low KH, Hao Yong Yu. Development of a lower extremity exoskeleton for human performance enhancement. In: 2004 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) [Internet]. Sendai, Japan: IEEE; 2004. p. 3889–94. Available from: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=1390021

105. Zoss AB, Kazerooni H, Chu A. Biomechanical design of the Berkeley lower extremity exoskeleton (BLEEX). IEEE/ASME Trans Mechatronics [Internet]. 2006 Apr;11(2):128–38. Available from: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=1618670

106. Technaid S.L. Exo-H3 Main Features [Internet]. 2021 [cited 2022 Aug 21]. Available from: www.technaid.com-info@technaid.com

107. Technaid - Leading Motion. Exoesqueleto Exo-H3 [Internet]. 2020 [cited 2020 Jul 28]. Available from: https://www.technaid.com/es/productos/robotic-exoskeleton-exo-h3/

108. Gil-Castillo J, Barria P, Aguilar Cárdenas R, Baleta Abarza K, Andrade Gallardo A, Biskupovic Mancilla A, et al. A Robot-Assisted Therapy to Increase Muscle Strength in Hemiplegic Gait Rehabilitation. Front Neurorobot [Internet]. 2022 Apr 29;16. Available from: https://www.frontiersin.org/articles/10.3389/fnbot.2022.837494/full

109. Copilusi C, Dumitru S, Geonea I, Ciurezu LG, Dumitru N. Design Approaches of an Exoskeleton for Human Neuromotor Rehabilitation. Appl Sci [Internet]. 2022 Apr 13;12(8):3952. Available from: https://www.mdpi.com/2076-3417/12/8/3952

doi: 10.25100/iyc.v27i1.14594

110. de Miguel-Fernández J, Lobo-Prat J, Prinsen E, Font-Llagunes JM, Marchal-Crespo L. Control strategies used in lower limb exoskeletons for gait rehabilitation after brain injury: a systematic review and analysis of clinical effectiveness. J Neuroeng Rehabil [Internet]. 2023 Feb 19;20(1):23. Available from: https://doi.org/10.1186/s12984-023-01144-5

doi: 10.25100/iyc.v27i1.14594