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REVIEW

Exploring Control Approaches for Robot-Based Gait Rehabilitation and Locomotion Assistance: A Comprehensive Review

Exploración de enfoques de control para la rehabilitación de la marcha y asistencia a la locomoción basada en robots: Una revisión exhaustiva

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Abstract

Context: Robot-assisted gait rehabilitation is a rapidly evolving field that aims to enhance therapeutic outcomes through the integration of advanced robotic systems. These systems reduce the physical burden on therapists while enabling intensive and repetitive patient training. However, current methods often require manual adjustments tailored to individual gait patterns, limiting their generalizability and efficiency.
Objective: This paper provides a comprehensive review of control approaches for robot-based gait rehabilitation and locomotion assistance, focusing on improving adaptability and human-robot synchronization. The goal is to identify effective techniques and methods that optimize exoskeleton performance and improve patient outcomes.
Methodology: A state-of-the-art review was conducted through a structured literature search across multiple scientific databases to identify research on lower-limb exoskeletons, centering on control strategies for robot-assisted gait rehabilitation. The search initially employed broad keywords such as “lower limb exoskeletons,” “extremity lower exoskeletons,” and “lower limb robotic exoskeletons,” among others. It was then refined using more specific terms including “lower limb exoskeleton control,” “assisted gait control,” “assistance control strategy,” “wearable robots control,” and “robotic rehabilitation,” among others. Well-defined inclusion criteria ensured thematic relevance, methodological rigor, and comprehensive coverage of recent advancements. A total of 77 studies meeting these criteria were analyzed to identify and categorize control approaches, and to discuss their scope, advantages, and

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limitations rather than directly assessing their clinical effectiveness or patient outcome improvements. Future research should focus on data-driven control methods to address individual variability and improve exoskeleton adaptability.
Results: The review highlights a taxonomy of essential control strategies for robot-assisted gait, such as trajectory tracking based on position, force-impedance control, control driven by bio-signals, and adaptive control techniques. Real-time adaptive strategies, such as Velocity Field Control and Assist-As-Needed approaches, demonstrate strong potential for improving synchronization and reducing manual tuning requirements.
Conclusions: Adaptive control strategies, particularly Assist-As-Needed controllers, are effective in encouraging active patient participation and optimizing rehabilitation outcomes.
Financing: This research work received funding from Universidad del Valle under the project *"Plataforma tecnológica modular para la valoración objetiva de la marcha humana"* (C.I. 21259) and from the Ministry of Science, Technology, and Innovation (Minciencias - Open call 647).
Keywords: Estrategia de control adaptativo, Control Assist-As-Needed, Interacción Humano-Robot, Sincronización Humano-Robot, Exoesqueleto de miembros inferiores, Rehabilitación de la marcha asistida por robots.

Resumen

Contexto: La rehabilitación de la marcha asistida por robots es un campo en rápida evolución que busca mejorar los resultados terapéuticos mediante la integración de sistemas robóticos avanzados. Estos sistemas reducen la carga física sobre los terapeutas y permiten entrenamientos intensivos y repetitivos para los pacientes. Sin embargo, los métodos actuales suelen requerir ajustes manuales adaptados a los patrones de marcha individuales, lo que limita su generalización y eficiencia.
Objetivo: Este artículo presenta una revisión integral de los enfoques de control utilizados en la rehabilitación y asistencia de la marcha mediante robots, con énfasis en mejorar la adaptabilidad y la sincronización humano-robot. El objetivo es identificar técnicas y métodos efectivos que optimicen el desempeño de los exoesqueletos y contribuyan a mejorar los resultados en los pacientes.
Metodología: Se realizó una revisión del estado del arte a través de una búsqueda estructurada de literatura en múltiples bases de datos científicas para identificar investigaciones sobre exoesqueletos de miembros inferiores con enfoque en estrategias de control para la rehabilitación robótica de la marcha. La búsqueda inicial utilizó palabras clave generales como "lower limb exoskeletons", "extremity lower exoskeletons" y "lower limb robotic exoskeletons", entre otras. Posteriormente, se refinó empleando términos más específicos, incluidos "lower limb exoskeleton control", "assisted gait control", "assistance control strategy", "wearable robots control" y "robotic rehabilitation", entre otros. Se aplicaron criterios de inclusión claramente definidos que aseguraron la relevancia temática, el rigor metodológico y la cobertura de los avances más recientes. Un total de 77 estudios que cumplían con estos criterios fueron analizados para identificar y categorizar enfoques de control, así como para discutir su alcance, ventajas y limitaciones, más que para evaluar directamente su efectividad clínica o su impacto en los resultados de los pacientes. Se sugiere que futuras investigaciones se centren en métodos de control basados en datos para abordar la variabilidad individual y mejorar la adaptabilidad de los exoesqueletos.
Resultados: La revisión resalta una taxonomía de estrategias de control esenciales para la rehabilitación robótica de la marcha, como el seguimiento de trayectoria basado en posición, el control de fuerza- impedancia, el control basado en bioseñales y las técnicas de control adaptativo. Las estrategias adaptativas en tiempo real, como Velocity Field Control y los enfoques de Assist-As-Needed, muestran un alto potencial para mejorar la sincronización y reducir la necesidad de ajustes manuales. Conclusiones: Las estrategias de control adaptativo, especialmente el control Assist-As-Needed, resultan efectivas para fomentar la participación activa del paciente y optimizar los resultados en los procesos de rehabilitación.

Conclusiones: Este trabajo de investigación recibió financiamiento de la Universidad del Valle, bajo el proyecto *"Plataforma tecnológica modular para la valoración objetiva de la marcha humana"* (C.I. 21259), y el Ministerio de Ciencia, Tecnología e Innovación (Convocatoria abierta 647).

Palabras clave: Estrategia de control adaptativo, Control Assist-As-Needed, Interacción Humano-Robot, Sincronización Humano-Robot, Exoesqueleto de miembros inferiores, Rehabilitación de la marcha asistida por robots.

Introduction

Rehabilitation engineering applied to human gait is a rapidly growing field that offers innovative ways to automate therapeutic interventions. Robotic rehabilitation systems reduce the physical strain on therapists while allowing them to focus on clinical protocols that promote motor relearning and coordinated movement. Key features include body weight support to reduce joint pressure, generation of gait patterns tailored to patient anthropometry, and active or passive participation through human–robot interaction (1–3). These systems also quantify motor recovery by evaluating force distribution, dynamic interactions, and joint angles.

In the medium term, the adoption of such technologies in rehabilitation centers could help optimize therapeutic resources and reduce long-term care costs. However, the acquisition and maintenance of robotic systems remain expensive, particularly in private centers where therapy fees may be unaffordable for vulnerable populations. Achieving real accessibility therefore requires not only technological innovation but also the development of public health policies, financing mechanisms, and scalable low-cost solutions to ensure equitable access to these technologies, especially in low- and middle-income settings.

Integrating robotics into gait rehabilitation offers a transformative solution for mobility impairments. Traditional methods require significant therapist effort and often lack the precision needed for optimal recovery. Robotic systems provide an efficient alternative by combining advanced control strategies with patient-specific adaptability. They enhance therapy while supplying valuable data for monitoring progress and tailoring interventions (4). As demand grows for affordable rehabilitation, robotic-assisted gait therapy bridges the gap between clinical needs and technological innovation.

This paper presents a comprehensive review of state-of-the-art control approaches for robot-based gait rehabilitation and locomotion assistance, focusing on their applications, scope, advantages, limitations, and potential to support clinical translation. It emphasizes the classification and analysis of control strategies to provide a structured perspective that guides future developments and facilitates the integration of these technologies into rehabilitation practices.

The second section outlines the methodology used to categorize control approaches, including trajectory tracking based on position, force-impedance control, control driven by bio-signals, adaptive control methods, and strategies for human-robot synchronization. The third section explores the foundational concepts underlying robot-assisted rehabilitation, focusing on key areas such as human-robot interaction, compliant mechanics, backdrivability, control modes, and performance indicators. The fourth section presents a detailed analysis of the results and discusses their implications, followed by a concluding section summariing the key findings of the review.

Methodology

A scoping review of the literature was conducted to identify key areas of interest and refine the objectives and scope of their analysis. This initial exploration established the foundation for defining the aim of the review and ensuring a focused approach. Given the rapid advancements in exoskeleton technology in recent years, this review places particular emphasis on incorporating the most recent studies. However, to account for the complexity and historical development of the field, a broader timeframe was adopted, covering publications from the past 14 years.

The methodological framework comprised a systematic search across multiple academic databases and sources, including ScienceDirect, Springer Nature, MDPI, IEEE/ASME, Frontiers, Elsevier, Taylor & Francis, Scopus, Sage, John Wiley & Sons, ResearchGate, and Google Scholar. This process aimed to identify all relevant technologies and studies related to lower-limb exoskeletons. The initial search employed the primary keywords "lower limb exoskeletons," "extremity lower exoskeletons," and "lower limb robotic exoskeletons." To refine the search and manage the extensive volume of available data, additional filtering keywords were applied, such as "lower limb exoskeleton control," "assisted gait control," "assisted gait controller," "assistance control strategy," "wearable robots control," "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," and "assisted gait rehabilitation."

This approach yielded a substantial number of candidate papers for further analysis. Each paper was meticulously reviewed 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 papers for this state-of-the-art review was guided by well-defined inclusion criteria designed to ensure a comprehensive and high-quality analysis. First, thematic relevance was prioritized by selecting studies that directly addressed the research topic—robot-assisted gait control—and its key subthemes (e.g., impedance control, EMG-based control, and adaptive strategies). Second, scientific rigor was ensured by focusing on peer-reviewed articles published in indexed journals (Scopus or Web of Science) that demonstrated methodological robustness, defined by (i) a clear and reproducible experimental or analytical design, (ii) detailed system or sample descriptions, (iii) the use of validated measurement or control techniques, and (iv) transparent reporting of data analysis procedures. Third, publication date was considered to ensure coverage of the most recent developments (2010–2025), while including seminal works critical to understanding the field's historical evolution. Fourth, originality and contribution were assessed by identifying studies that employed novel control strategies, presented innovative implementations, or demonstrated clinical or technical advances with measurable impact. Fifth, geographic and cultural diversity was encouraged by including studies from different continents and socio-cultural contexts, as long as they met the core technical criteria, to provide a broader and more representative perspective of global research. Sixth, source reliability and citation impact were ensured by prioritizing publications from reputable journals with recognized academic influence—based on indexing, impact factor, and/or citation count—along with well-established conference proceedings. Finally, a diverse range of scholarly outputs—original research articles, systematic reviews, surveys, book chapters, patents, conference proceedings, meta-analyses, and technical reports—were included, provided they made a relevant and verifiable contribution to the topic. These operationalized criteria strengthen the transparency and replicability of the selection process, ensuring a balanced, comprehensive, and critical synthesis of the literature.

This state-of-the-art review does not intend to be inherently innovative but rather to provide an original perspective that enables the systematic categorization and the critical interpretation of existing advancements in the field. It also seeks to identify emerging trends and highlights underexplored or unrecognized areas, which are crucial for guiding future research. By compiling and analyzing the main studies, trends, technologies, and relevant theories from reliable sources, this work makes a significant contribution to advancing global understanding of robot-assisted human gait rehabilitation and its control strategies.

Foundational concepts in robot-assisted gait

In this section, fundamental concepts relevant to human-robot interaction, compliant mechanics, backdrivability, control modes, and performance indicators are reviewed, with a focus on assistance control for robot-based rehabilitation.

Human-robot interaction

Human-Robot Interaction (HRI) in robot-assisted gait refers to the combined torques produced by the human user and the exoskeleton at a lower-limb joint. It represents the sum of forces acting on the coupled human–exoskeleton system, resulting from physical interaction between the user, the robot, and the environment.

As shown in Figure **1**, the coupled system can be modeled as two interconnected rotational mass-spring-damper systems. The impedance parameters of both the human joint and the exoskeleton are critical to this interaction. The coupling is typically considered rigid due to the mechanical power transmission between the joint axes, generating an interaction torque τ_i at the joint.

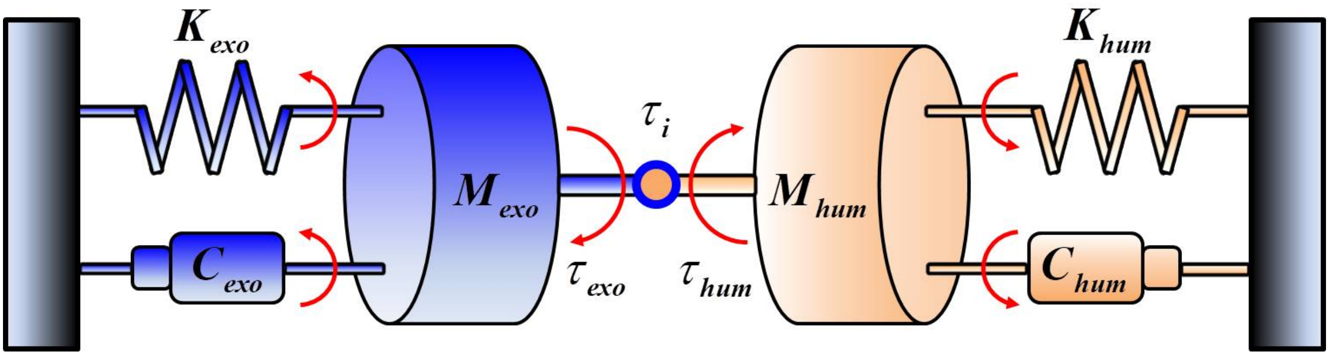

Figure 1. Rigidly coupled human-exoskeleton system (5)

The HRI defines the relationship between torque/force and angular displacement and it can be regulated through a hybrid control scheme (6), Figure **2**.

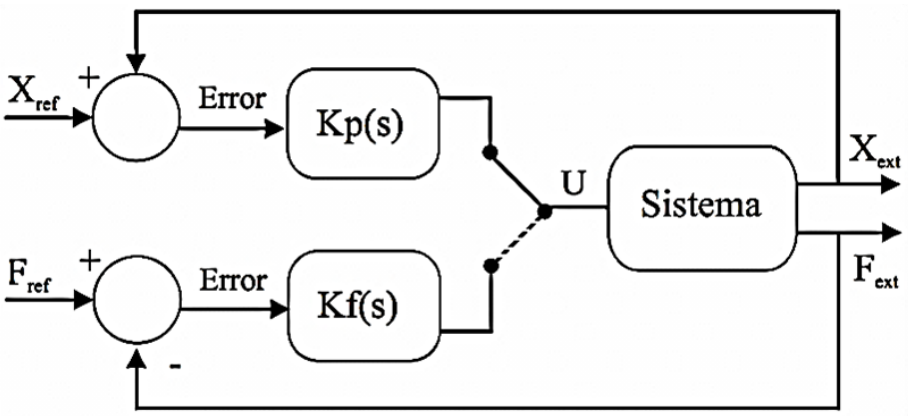

Figure 2. Hybrid control loop to regulate the angular displacement and force of the coupled human-exoskeleton system (6)

The HRI issue can be addressed through the impedance control method, which is based on regulating the mechanical impedance parameters—inertia, damping, and elastic stiffness—of the coupled human-exoskeleton system as defined in Equation (1) (5).

$$[M_{exo} + M_{hum}]\,\ddot{\theta} + [C_{exo} + C_{hum}]\,\dot{\theta} + [K_{exo} + K_{hum}]\,\theta = \tau \tag{1}$$

where,

θ, $\dot{\theta}$, $\ddot{\theta}$: Vectors for angular position, velocity, and acceleration in both the exoskeleton and the human joints.
τ: Vector for net torque in the joint.
M_{exo}, M_{hum}: Vectors for moment of inertia in both the exoskeleton and the human joints, respectively.
C_{exo}, C_{hum}: Vectors for damping in both the exoskeleton and the human joints, respectively.
K_{exo}, K_{hum}: Vectors for elastic stiffness in both the exoskeleton and the human joints, respectively.
$[M_{exo} + M_{hum}]\,\ddot{\theta}$: Torque matrix due to moment of inertia, [Nm].
$[C_{exo} + C_{hum}]\,\dot{\theta}$: Torque matrix due to viscous friction, [Nm].
$[K_{exo} + K_{hum}]\,\theta$: Torque vector due to elastic stiffness, [Nm].

The dominant dynamics of the joint can be described by a linear relationship between angular displacement and net torque, as expressed in Equation (2), where individual impedance parameters are crucial. This dynamic behavior results from a combination of factors, including the low-level neural reflexes, the viscoelastic properties of muscles, the intrinsic inertia of the joint, and passive mechanical contributions from soft tissues, skin, ligaments, and tendons. In (7), the concept of mechanical impedance was used to model the dynamic behavior of the musculoskeletal system.

$$\frac{\theta(s)}{\tau(s)} = \frac{1}{[M_{exo} + M_{hum}]\,s^2 + [C_{exo} + C_{hum}]\,s + [K_{exo} + K_{hum}]} \tag{2}$$

Figure **3** illustrates a closed-loop control scheme designed to modulate the impedance of the human- exoskeleton system. In this configuration, the desired (virtual) mechanical impedance is achieved by adjusting the effective inertia, damping, and stiffness through the modulation of the coefficients m, c, and k, respectively.

The virtual mechanical impedance in the human-exoskeleton system is defined in Equation (3) as a function of angular displacement, θ, and angular velocity, $\dot{\theta}$, respectively. In the literature, the related concepts of impedance and admittance describe the relation between force and speed instead of position and thus relate the power (8).

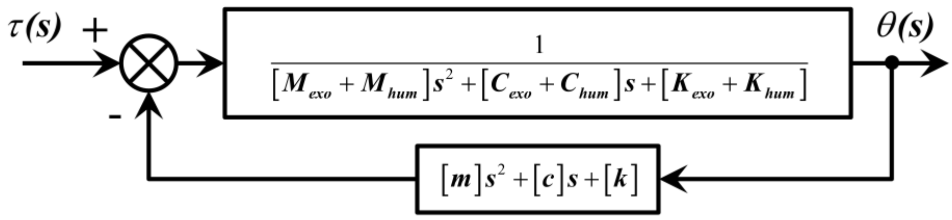

Figure 3. Closed-loop control for modulating impedance in the human-exoskeleton system (5)

$$
\begin{aligned}
Z_{\theta}(s) &= [M_{exo} + M_{hum} + m]\, s^2 + [C_{exo} + C_{hum} + c]\, s + [K_{exo} + K_{hum} + k] \\
Z_{\dot{\theta}}(s) &= [M_{exo} + M_{hum} + m]\, s + [C_{exo} + C_{hum} + c] + \frac{[K_{exo} + K_{hum} + k]}{s}
\end{aligned}
\tag{3}
$$

HRI dynamics are inherently non-linear, as the passive impedance properties of the musculoskeletal system vary non-linearly with the body's kinematic state. Humans modulate impedance through muscle co-contraction and co-activation when interacting with external forces (6). Estimating HRI is essential for designing effective assistance control strategies, as it quantifies human and robot contributions, allowing tailored robotic assistance during rehabilitation training. To estimate HRI, the study in (9) presents a scheme of a Disturbance Observer (DOB) that estimates the interaction torque between the robot and the wearer without force sensors. This approach is particularly useful for detecting human intention and corresponds to a model-based torque control framework, as shown in Figure **4**. This paper explores control approaches implemented in robotic devices for gait assistance, utilizing interaction torque as a feedback signal, as detailed in the subsection titled *'Adaptive Control Based on Patient Movement Ability*, which focuses on tailoring robotic assistance to the user's specific needs.

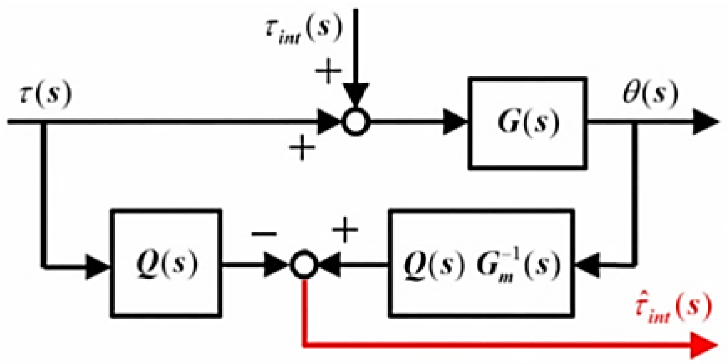

Figure 4. Disturbance observer to estimate the interaction torque (9). The figure was adjusted by the authors of this paper to illustrate the estimation of the interaction torque, $\hat{\tau}_{\text{int}}$, (5)

The compliant mechanics

De Schutter (10) defined compliant motion control as "any robot motion during which the end effector trajectory is modified, or even generated, based on online sensor information." Compliant mechanics are thus directly related to HRI, particularly in rehabilitation robotics, where compliant controllers adjust mechanical impedance in stiff or soft joints of the robotic system. Compliant mechanics are also referred to as soft, elastic, or flexible mechanics. Mechanical and stiffness compliance describe the static displacement-force relationship, whereas impedance and admittance define the dynamic relationship between force and displacement. Table 1 summarizes the control types by mechanical properties, control method, and approach.

Table 1. Mechanics and Control Strategies: Classification Based on Compliance (C) and Non-Compliance (NC) in Robotic Systems

Control type	Mechanics	Control	Approach
Control based on position of rigid joints	NC	NC	Control based on position tracking.
Control based on position of flexible joints	C	NC	Control based on position tracking with elasticity regulation.
Adaptive control of rigid joints	NC	C	Virtual stiffness.
Adaptive control of flexible joints	C	C	Equilibrium-controlled stiffness, and programmable springs.
Control of mechanically adjustable compliance joints	Adj. C	C	Position and stiffness are controlled independently.

Source: (8)

Backdrivability

Backdrivability is the mechanical propriety of a motor drive system that indicates whether its motion can be easily reversed (11, 12). Actuators composed of a motor, rigid transmission, and stiff or soft interface, exhibit backdrivability that depends on transmission efficiency and actuator impedance. Figure **5** illustrates three typical actuator configurations related to backdrivability. In Figure **5**(a), the motor is *inherently backdrivable*, meaning it can be moved both by electrical energy and external forces, allowing natural interaction with the environment. In Figure **5**(b), the motor is *not-backdrivable* due to the high stiffness of the transmission, which prevents movement in the reverse direction. Finally, configuration Figure **5**(c) shows a non-backdrivable motor with a torque control loop, which enables the system to emulate backdrivability and respond to external forces, compensating for the lack of mechanical reversibility. These three configurations highlight how transmission properties and control strategies influence actuator behavior during human-robot interaction.

Backdrivability in stiff or soft actuators, together with mechanical compliance, is closely linked to force and position control. In ideal position control, infinite stiffness (zero compliance) ensures accurate tracking and disturbance rejection. Conversely, force control requires zero stiffness (infinite compliance) to prevent force variations due to displacement (13). Calanca *et al.* (8) reviewed algorithms for compliant control in stiff and fixed-compliance robots.

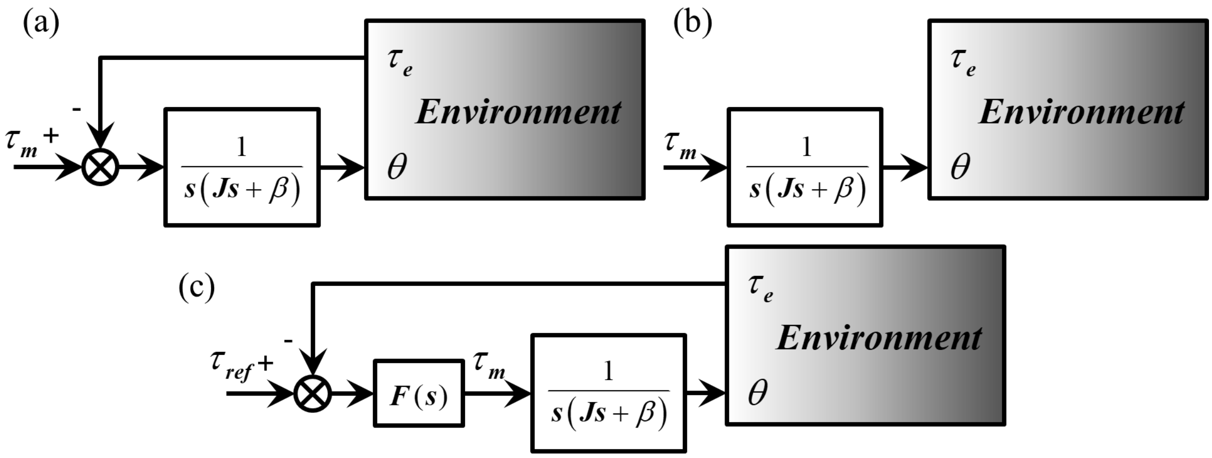

Figure 5. Backdrivable motor model. Backdrivability is represented by the difference between the environmental torque, τ_e, and motor torque, τ_m, which is then connected to the motor input. (8). (a) Fully backdrivable motor, (b) Non-backdrivable motor, and (c) Fully non-backdrivable motor with an outer torque loop. The figures were adapted by the authors of this paper to illustrate the effect of the viscous friction, $\beta\dot{\theta}$, (5)

Control modes

The therapist's expertise and the patient's level of disability determine the appropriate control mode (also referred to as training mode)—passive or active (14), as illustrated in Figure **6**. Although the earliest approaches identified only these two main modes, later developments expanded the classification to include active constrained and bi-manual modes. In this work, these four control modes are adopted as the conceptual framework for robot-assisted gait training. The main control modes for robot-assisted rehabilitation are summarized below (14–16):

- **Passive mode:** Referred to as Inactive, Position-Control, or Robot-in-Charge mode, this approach involves the robot following pre-defined trajectories to move the patient's lower limbs. While it is effective in preventing muscle contractures, its ability to stimulate motor recovery remains uncertain.

- **Active mode:** Known as Active Assisted, Therapist-in-Charge mode or Patient-in-Charge, this approach involves the robot providing partial assistance to the patient's movement. The robot adjusts its trajectory or assistance force in response to the patient's force contribution, making it particularly useful for patients who have difficulty completing movements toward a target.
- **Active constrained mode:** Known as Challenge-based, Active-Constrained, or Perturbation mode, this approach involves the robot applying resistance forces during the patient's movements to increase training difficulty. The robot executes specific movements when the patient generates a correctly oriented force. By perturbing the patient's movements, the robot stimulates error correction mechanisms, which are crucial for motor control.
- **Bi-manual mode:** Also referred to as isotonic or isokinetic modes, these are inspired by manual therapy techniques. Movements performed by the healthy limb are mirrored and applied symmetrically to the injured limb, creating mirror-image movements.

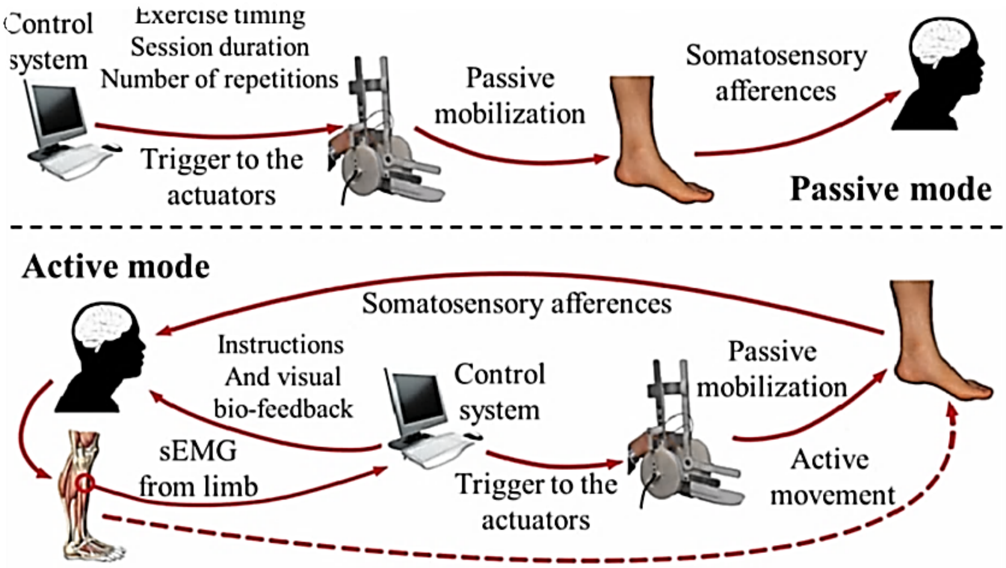

Figure 6. Control modes for robot-assisted rehabilitation: Passive and active (14)

Performance indicators

The current literature presents a plethora of methods, variables and protocols used to quantify the performance of robotic exoskeletons. This section highlights the most relevant aspects presented in the review "Performance Evaluation of Lower Limb Exoskeletons: A Systematic Review" (17). The Performance Indicators (PEIs) outlined below are helpful for assessing the effectiveness of assistance controllers implemented in robotic systems designed for human gait rehabilitation. The tasks of the robotic exoskeleton are focusing on flat ground walking, treadmill walking, weight-bearing walking, slope walking, sit-to-stand and stand-to-sit transitions, backward stepping, and lateral stepping.

The most representative performance indicators are categorized into three main groups:

1. **Goal-level variables:** These encompass minimum time or maximum speed, achievable distance, stability, versatility, endurance, and dependability.

2. **Kinematics/Kinetics variables:** This category includes spatiotemporal parameters, joint or limb kinematics and kinetics, coordination, symmetry, and human likeness.

   - ***Joint or limb kinetics:*** Global power, torques, forces, and ground reaction forces (GRF).
   - ***Symmetry:*** Joint trajectory deviation and GRF propulsion impulse.

3. **Human-robot interaction variables:** Encompass metabolic cost, muscle effort, ergonomics, interaction forces, comfort, safety, and cognitive effort.

   - ***Metabolic Cost:*** Heart rate, heart rate variability, oxygen consumption, blood lactate concentration, carbon dioxide production, biological power, metabolic power, fatigue, work, and calorimetry.
   - ***Muscle Effort:*** Visual Analogue Scale of Fatigue (VAS-F), muscle alteration rates, muscle activity recognition, Posterior onset detection, and biological joint torques.
   - ***Comfort:*** User comfort perception, clinical questionnaires, pain scales, usability, acceptability, and functionality.
   - ***Interaction Forces:*** Power delivered to the robot, the interaction forces between the human and the robotic system, and forces transmitted through the interface.
   - ***Ergonomics:*** Relative positioning between the human and the robot, displacements at the interface, alignment with anthropometric data, and adaptability to users of different heights.
   - ***Safety:*** Blood pressure, number of falls, heart rate, clinical questionnaires, and post-use assessments of skin, spine, and joint status.
   - ***Cognitive Effort:*** Psychophysiological PEIs such as attention, stress, and perceptibility.

Pinto-Fernandez *et al.* (17) noted that metabolic cost alone is insufficient to evaluate interaction performance. Correlating interaction forces or torques with subjective measures provides a more accurate reflection of the level of assistance provided by the exoskeleton.

The authors in (18) proposed two indices—the Normalized Energy Consumption Index (NECI) and walking distance over a fixed time—to evaluate performance under different admittance parameters. NECI represents energy expenditure at the subject's joint. Additionally, Huo *et al.* (19) reviewed performance assessment methods to evaluate the acceptability of lower-limb exoskeletons by potential users, focusing on metabolic cost, gait biomechanics, and muscle activity analyses.

Results

The results of this state-of-the-art review are derived from a systematic and structured literature search conducted according to predefined inclusion and exclusion criteria. This process was designed to ensure methodological transparency, traceability, and replicability. The initial search covered multiple high-impact academic databases, including ScienceDirect, IEEE Xplore, Springer, MDPI, Scopus, and other reputable sources. Articles were progressively filtered through duplicate removal, thematic screening, and the application of explicit inclusion and exclusion criteria, resulting in a focused selection of studies directly relevant to control strategies for lower-limb exoskeletons. The flow of article selection and the number of records retained at each stage are summarized in Table 2.

Table 2. Results of the literature search and selection process

Database / Source	**Records identified**	**Duplicates removed**	**Excluded (did not meet inclusion criteria)**	**Included in the review**
ScienceDirect	58	6	34	18
IEEE Xplore / IEEE–ASME	45	3	28	14
Springer Nature / Elsevier / Taylor & Francis	62	7	39	16
MDPI / Frontiers / Wiley / Sage	37	5	20	12
Scopus	26	4	15	7
ResearchGate / Google Scholar	48	10	28	10
Total	**276**	**35**	**164**	**77**

An initial search across multiple academic databases yielded 276 records. Duplicates (n = 35) were removed using Mendeley reference manager and manual cross-checking. The remaining 241 records were screened based on the predefined inclusion criteria: thematic relevance, methodological rigor, publication quality, originality and contribution, geographical diversity, and citation impact. Articles were excluded if they did not meet these criteria, specifically when (i) they lacked methodological clarity or did not provide sufficient technical or clinical detail, (ii) they were not peer-reviewed or indexed, or (iii) their scope was unrelated to control strategies for lower-limb exoskeletons. After applying the exclusion criteria (n = 164), 77 studies met the eligibility requirements and were included for full-text analysis. These studies constitute the evidence base presented and analyzed in the Results and Discussion sections. This transparent selection process reinforces the methodological rigor of the review and facilitates its reproducibility by other researchers.

Building upon this selection of studies, the following sections present the results and discussions derived from the analysis of control approaches for robot-based gait rehabilitation and locomotion assistance, as well as methods for human-exoskeleton synchronization. The findings are organized to highlight the effectiveness, challenges, and innovations of various control methods, including trajectory tracking based on position, force- impedance control, control driven by bio-signals, and adaptive control methods. Additionally, the discussion explores approaches for achieving seamless human-robot synchronization, which is critical for enhancing patient outcomes and ensuring natural interaction during rehabilitation and the assistance. Figure **7** provides a taxonomy of control strategies for robot-assisted gait. This synthesis identifies key trends, gaps in the literature, and future research directions to advance robotic gait rehabilitation.

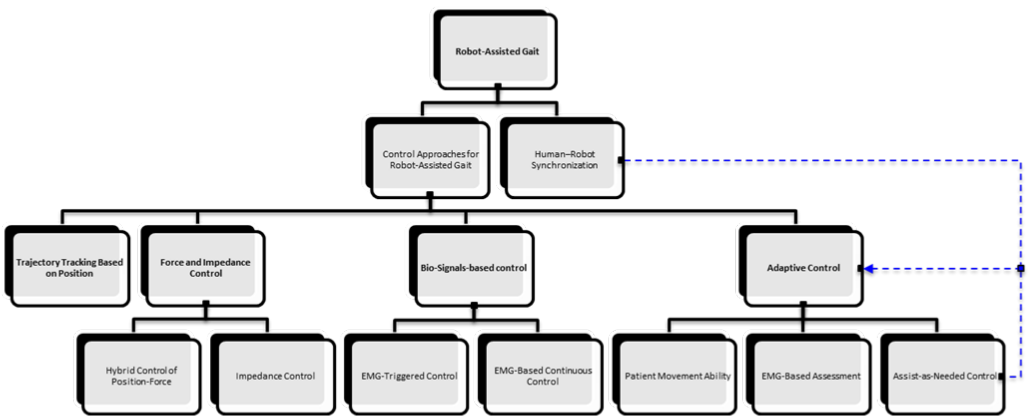

Figure 7. Taxonomy of control approaches for robot-assisted gait

Control approaches for robot-assisted gait

Robots designed for rehabilitation and assistance gait can be categorized based on their control architecture or the implementation of specific control methods. Lately, strategies such as hybrid control, adaptive control, Assist-As-Needed (AAN) control, and human-robot interaction control have been widely integrated into robotic systems to enhance the effectiveness of gait rehabilitation in patients. Current research suggests that bio-signal- and biofeedback-based control techniques are effective and represent an important area for further study (20).

The interaction between the user and the robotic device creates a combined human-machine system, in which the operator becomes an integral part of the control loop, commonly referred to as Human-in-the-Loop (HITL) control. The purpose of this coupled system is to make that the human and the robot work in a coordinated way to complete tasks (21). The work (22) shows a classification of control strategies for lower extremity exoskeletons into three categories according to different applications: gait rehabilitation, human locomotion assistance, and human strength augmentation. Similarly, (23) discusses various control strategies for knee exoskeletons, while the review in (24) details control aspects of ankle rehabilitation robots, including motion/force control strategies (inner loop position/velocity control, and inner loop force/torque control) and interaction controllers for rehabilitation robots (basic interaction controllers, and higher level interaction control). Likewise, the survey (25) discusses two control schemes; the first is a model-based control scheme, which relies on algorithms derived from either the kinematic or dynamic model of the robotic system, including methods such as active impedance control, admittance control, biosignal-integration-based control, optimal control, and machine learning; the second scheme uses a trial-and-error learning method, which does not require an analytical model of the system to evaluate its control performance. A systematic review (4) highlights that exoskeletons serve different purposes depending on the rehabilitation approach, influencing whether control strategies assist or challenge patients. Strategies include assistive controllers for tasks such as sit-to-stand and gait stability, challenge-based controllers that strengthen muscles or increase movement variability, and adaptive controllers that adjust parameters to meet individual patient needs. The review also assesses the clinical efficacy of these strategies in lower-limb exoskeletons for patients recovering from brain injuries.

Control approaches such as model-based, interaction-based, task-based, and hierarchical control (26) can be applied independently or in combination to implement Assist-As-Needed (AAN) strategies. In the literature, several control methods have been employed to support gait rehabilitation and locomotion assistance, including trajectory tracking based on position, force and impedance control, bio-signal driven control, and adaptive control techniques. Among these strategies, adaptive control has emerged as a key approach for achieving human–robot synchronization, enabling robotic systems to dynamically adjust assistance levels in response to the user's performance and timing.

To provide a structured overview of these approaches, the studies included in this review were systematically analyzed and grouped according to their primary control strategy. Table 3 summarizes the most representative methods identified, together with their corresponding clinical or pilot applications, objectives, and reported patient outcomes. This synthesis highlights the predominant trends in robot-assisted gait rehabilitation and establishes a foundation for the subsequent sections, where each control method is examined in greater detail.

Table 3. Control Methods in Robot-Assisted Gait Rehabilitation: Applications, Objectives, Patient Outcomes, and References

Control method	Clinical / Pilot applications	Objective / Patient outcomes	References
Position / Trajectory Tracking	Lokomat systems, treadmill-based rehabilitation, passive guidance devices	Provide predefined gait trajectories, improve gait patterns, minimize therapist effort, increase endurance	Bernhardt *et al*. (2005); Riener *et al*. (2005); Koopman *et al*. (2013); Ma *et al*. (2013); Hidler *et al*. (2009); Mao *et al*. (2015); Israel *et al*. (2019); Buesing *et al*. (2015); Banala *et al*. (2009); Freivogel *et al*. (2009); Bruni *et al*. (2018); Calabrò *et al*. (2016); Westlake & Patten (2009); Swinnen *et al*. (2010); Contreras-Vidal *et al*. (2016); Duschau-Wicke *et al*. (2010); others.
Force / Torque Control	Ankle and knee exoskeletons, torque-based actuators, human-in-the -loop devices	Regulate interaction forces, increase transparency and responsiveness, enhance user comfort and safety	Jamwal *et al*. (2015); Vallery *et al*. (2009); Shamaei *et al*. (2014); Saglia et al. (2013); Mao *et al*. (2015); Riener *et al*. (2010); Duschau-Wicke et al. (2010); Finley *et al*. (2015); Hidler *et al*. (2009); others.
Impedance / Admittance Control	Knee and hip exoskeletons, wearable assistive robots	Modulate impedance to adapt assistance level, improve comfort, promote active participation	Beyl *et al*. (2009, 2011); Hussain *et al*. (2013, 2016); Arevalo & García (2012); Calanca *et al*. (2016); Wolbrecht *et al*. (2008); Fleerkotte et al. (2014); Marchal-Crespo *et al*. (2017); others.
Assist-as-Needed (AAN)	Lokomat, gait training robots, cooperative devices	Adjust assistance based on performance, foster neuroplasticity, support motor relearning	Wolbrecht *et al*. (2008); Duschau-Wicke *et al*. (2010); Fleerkotte *et al*. (2014); Asl *et al*. (2017, 2018, 2020); Israel *et al*. (2019); others.
Bio-signal Driven Control (EMG/EEG/ECG)	EMG-based lower-limb exoskeletons, hybrid BMI systems	Detect user intention, enable intuitive control, increase voluntary activation	Cao *et al*. (2014); Yin *et al*. (2012); Charafeddine *et al*. (2019); Contreras-Vidal *et al*. (2016); otros.
Adaptive Control	Patient-specific adaptive exoskeletons, AAN integration, hybrid systems	Personalize assistance, improve gait symmetry, efficiency, engagement , and enhance human–robot synchronization	Hussain *et al*. (2016); Duschau-Wicke *et al*. (2010); Marchal-Crespo *et al*. (2017); Wolbrecht *et al*. (2008); Charafeddine *et al*. (2019); Saglia et al. (2013); Cestari *et al*. (2015); Miguel-Fernández *et al*. (2023); others.

Model-based / Optimal Control	Research-grade exoskeletons, control benchmarking	Increase accuracy, robustness, stability, energy efficiency	Chen *et al*. (2016, 2024); Harib *et al*. (2018); Tijjani *et al*. (2022); others.
Learning-based / Hybrid Control	Experimental exoskeletons integrating AI, adaptive impedance, and biosignals	Improve adaptability and personalization; enhance human-robot synchronization	Tijjani *et al*. (2022); Charafeddine *et al*. (2019); Cao *et al*. (2014); others.

- **Position-based trajectory tracking control:** This method is commonly used in early rehabilitation to assist impaired limbs through repetitive, consistent exercises. A primary challenge in this approach is designing an appropriate angular trajectory for the patient. While this control strategy enables repetitive passive training, its success depends on accurate trajectory generation and effective control performance (27). Nevertheless, it tends to restrict the patient's active involvement and initiative during therapy.

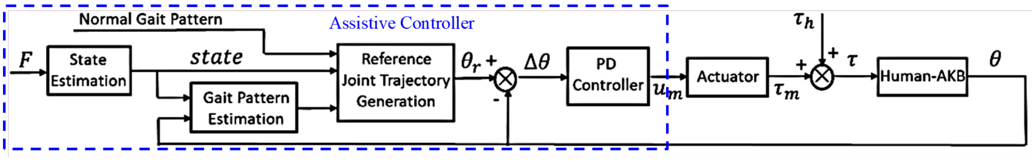

Figure 8. Control scheme of a powered knee orthosis for gait assistance, AKB (Assistive Knee Brace) (28)

In (29), a method for the online generation of trajectories applicable to hemiparetic patients is proposed; the desired positions and speeds for the affected leg are generated online based on the movements of the unaffected leg. Similarly, (30) implements a position-control scheme for patient-passive exercises. For knee rehabilitation exoskeletons with position-based trajectory tracking control, the wearer's knee joint can be controlled to follow a reference trajectory (28). Continuous and repetitive training is therefore achievable, as shown in Figure 8, with similar control structures have also been reported in (28,31,32). The research (33–35) take into account safety considerations during gait rehabilitation, because the robotic exoskeleton can track the reference trajectory while achieving a safe response due to large tracking errors.

- **Force and impedance control:** Developing a compliant active exoskeleton controller typically involves the use of force interaction controllers, which are commonly implemented as either impedance or admittance controllers. These are integrated within hierarchical control structures that include high-level and low-level controllers (36), with the overall goal of achieving precise and reliable control. This section explores assistance control strategies, focusing on approaches that incorporate segment force or joint motor torque. Key strategies include hybrid position-force control and impedance control, widely used in robotic and assistive applications:

Hybrid control of position-force: Rehabilitation protocols have traditionally incorporated position-based tracking control, which involves the execution of predefined trajectories with limited patient interaction. Hybrid position/force control introduces an additional force regulation loop that enables the modulation of interaction forces or torques during movement. This approach has been applied in several studies addressing lower limb strengthening protocols, where the robotic system follows a reference trajectory while regulating applied force, and a continuous switch can distribute the contribution between the position and force control loops.

The research in (37) presents the development of a hybrid controller of position/force with a fuzzy logic, its function is to restrict the movement in the desired direction and maintain a constant force along the direction of movement. The paper (38) shows that an arbitrary percentage of force assists the patient in order to walk.

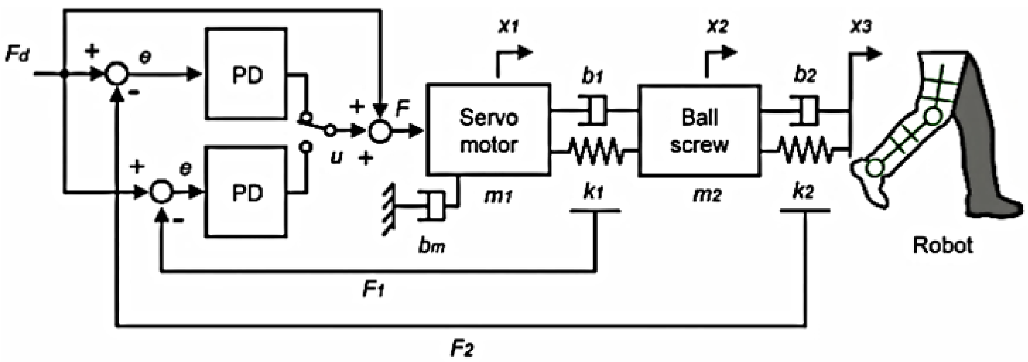

Figure 9. Force control diagram with two sets of PD plus feed-forward controllers (39)

In (39), the authors developed a hybrid position and force controller to minimize the interaction between the wearer and the knee exoskeleton (Figure **9**). The paper (40) proposed a control strategy based on a finite state machine, in which position control, force control, and damping control are adopted during each gait state. In (41), a position-based hybrid impedance control was applied to a lower-limb exoskeleton for patients who could follow the desired trajectory with moderate difficulty. Furthermore, in (42), a bio-inspired hybrid control strategy was introduced for the BATEX exosuit, addressing both the stance and swing phases of walking. During the swing phase, the motors are locked, transforming the Series Elastic Actuators into passive biarticular springs to enable natural leg motion.

This is complemented by a Force-Modulated Compliance controller that adjusts the stiffness of the artificial muscles during the stance phase based on ground reaction forces.

Impedance control: This strategy is used to regulate human–robot interaction by adjusting contact force and position in real time. It establishes interaction conditions that allow the robotic device to respond to patient movement and variations during rehabilitation. Impedance control is reported in multiple studies as a commonly implemented method in gait rehabilitation, where its primary role is to modulate interaction forces during training.

In (43), the robot joints employed impedance control to allow bidirectional mechanical interaction between the robot and the patient. The study in (44) proposes an adaptive impedance control scheme that adapts robotic assistance according to the disability level and patient participation (Figure **10**). Likewise, (45) details the development of an impedance controller for gait assistance using the LOPES exoskeleton. The authors in (46) present an approach that decodes a neuromuscular signal associated with the user's intended foot movement; using the exoskeleton's motors, the system moves the user's legs in real-time while providing sensory feedback; this combination enables real-time adjustments, resulting in a gait that closely mimics natural walking.

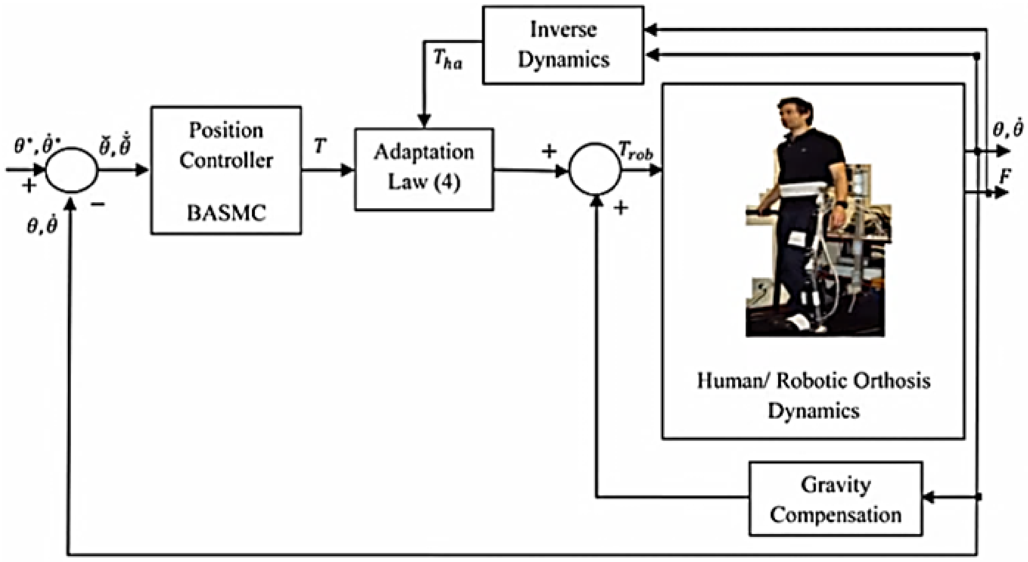

Figure 10. Adaptive impedance controller, which adjusts the robotic assistance based on human torque (44)

Also, the force/torque control is used in knee exoskeletons, since it can ensure the assistance of the wearer's knee movements. In (39, 47, 48) force controllers such as torque control, and positive-feedback force amplification control based on the Ground Reaction Forces (GRF) are developed.

- **Bio-signals-based control:** The acquisition of biological signals from the human body offers valuable insights into the dynamic of limb movements, enabling the robot to operate in a more intuitive and natural manner. This control strategy utilizes physiological signals acquired through electromyography (EMG), electrocardiography (ECG), and electroencephalography (EEG), as well as respiration rate (RR) and heart rate (HR), among others.

The research (49) explains a correlation between EMG signals, limb mobility, and muscle activity. Therefore, with the current processing techniques for bio-signals, the control of robots based on this type of signal has become an attractive research area (50, 51). Nowadays, bioelectric signals from the user's muscles are increasingly being integrated into the control systems of knee exoskeletons, enabling more intuitive and responsive assistance during rehabilitation. In (52), the authors proposed a stiffness control strategy for the knee exoskeleton based on the EMG analysis; (53) presented a method to generate the reference trajectory of the knee exoskeleton by mapping it to user EMG signals.

EMG-triggered Control: This control is based on the muscular activation of the limb to predict the patient's intention to move (54), since the EMG signals are generated before the muscular contraction of the limb; robot assistance is activated when an EMG signal threshold is reached; the patient starts the movement on own initiative, and there is no interaction until the next EMG trigger occurs. In (55), a neuro-fuzzy controller is built to decode human movement in advance through a fusion of fuzzy EMG signals (Figure **11**), and thus estimate the intention of human movement and proprioception, providing information about joint angles.

EMG-based continuous control: EMG-triggered control operates as an On-Off mechanism, limiting interaction despite reflecting patient intention. Continuous EMG-based control addresses this by using EMG signals to estimate joint angles or torques and provide proportional assistance, enabling uninterrupted patient-robot interaction during training.

Fan and Yin present a control technique for early progressive and active rehabilitation (56) (Figure **12**); they use a fusion of recorded information from electromyography and extended physiological proprioception of force-position. The study presented in (57) adapts co-contraction indexes for exoskeleton control and introduces a framework for designing

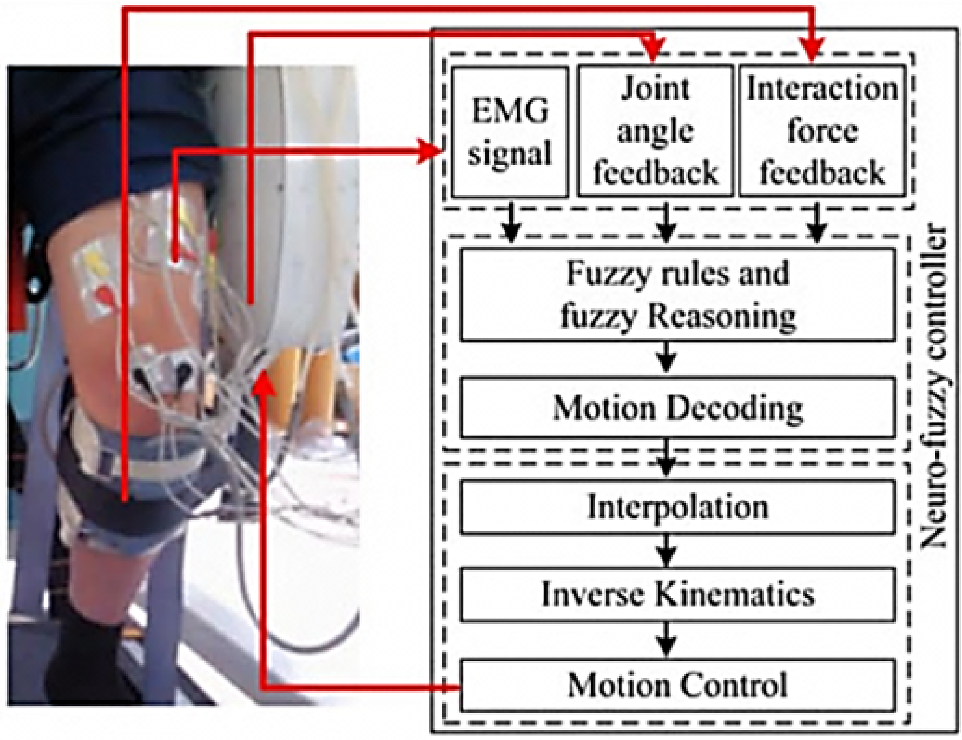

Figure 11. Neurofuzzy controller of the exoskeleton robot. The torque, speed, and position on the joints are fed back to the human (55)

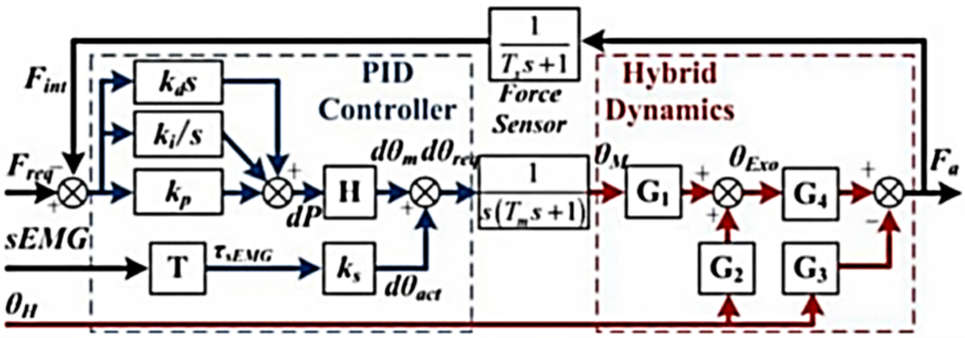

Figure 12. Control block diagram of active mode, the passive mode is controlled by a PID controller (56)

controllers using EMG signals and kinematic data; this approach captures patient-specific walking behavior, enabling interactive control without relying on a reference walking cycle.

- **Adaptive control strategies:** There is a notable distinction between the support offered by a therapist and that provided by a robotic assistant. Robotic systems are designed to adapt to each patient's specific needs and deliver support only when necessary, ensuring personalized and efficient rehabilitation. The authors in (58, 59) classified the most effective control strategies for robotic-assisted rehabilitation into three categories: impedance-based active control, EMG-based active control, and adaptive control based on patient conditions; also, these authors state that adaptive impedance control has a higher probability to achieve better effects in rehabilitation because the robot's behavior is flexible and adjustable to the skills, progress, and participation of the patient.

To enhance patient motivation and encourage active participation, researchers are implementing the AAN approach in robotic devices. This approach enables the system to dynamically adapt to the patient's capabilities, providing assistance only when necessary and avoiding the use of rigid, non-flexible control methods. The assistance controllers based on AAN control approach are also known as ”Patient-Cooperative”, ”Human-Centered” or ”Progressive” controllers (45). Also, In the technical review (60) the terms "Adaptive", "Impedance" and "Interactive" control schemes have been used with the purpose of AAN approach. In (20) the authors suggested a review of implementations of the AAN concept in robotic gait rehabilitation, which could help researchers to have a better understanding and benefit from its further development.

A state-of-the-art review of control strategies for robotic rehabilitation is presented in (59, 61) explains a patient-cooperative strategy that influences leg-movement synchronization along a physiological trajectory.

The following subsection shows a classification of adaptive control strategies using the AAN control approach, which is based on the patient's ability to move and an EMG-based assessment:

Adaptive control based on patient movement ability: The movement ability of a patient can be estimated from force/torque sensors (30, 44), quantitative efforts (62), and trajectory following error (63). Thus, an adaptive controller could allow adjusting the assisting force of the robot according to the physical movement capacity of the patient, (62), *i.e.*, this assistance controller makes the behavior of the robot more flexible and adjustable to the ability and participation of the patient. The robotic system therefore adjusts the level of assistance based on the patient's capacity to generate active force or correct following errors.

As proposed in (64), to enhance compliance in rehabilitation training, the robot must provide adaptable assistive support through a hierarchical, adaptive, patient-cooperative compliant control strategy designed to prioritize patient safety and comfort during rehabilitation exercises; in this approach, the motion trajectory of the lower-limb rehabilitation robot returns to the predefined reference path once the interaction force is no longer present.

(65) presents cooperative strategies to detect the voluntary efforts of patients. In (66), a model-based controller is used with an adaptive control approach to know the patient's capabilities and to be able to assist in the execution of movements. In (66), an impedance-control-based gait-pattern adaptation algorithm is developed (Figure **13**) where the Lokomat-patient interaction is minimal if the coupled system movement is completely synchronized.

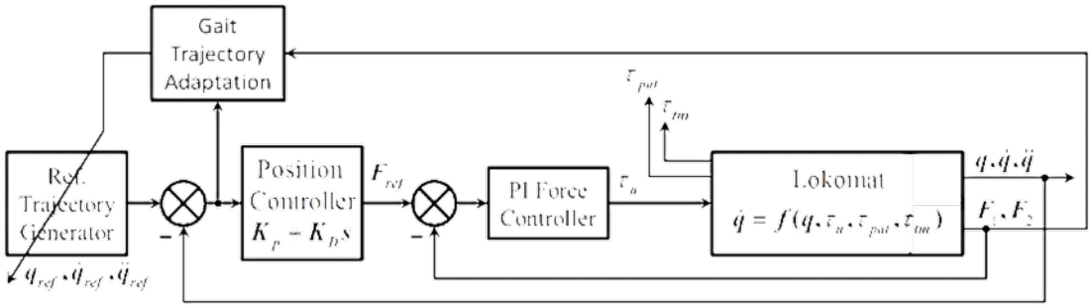

Figure 13. Lokomat, impedance-control-based gait-pattern adaptation controller (69)

The work (67) details an algorithm to generate an adaptive reference trajectory based on measured interaction force, and applying the necessary torque to complete gait (Figure **14**).

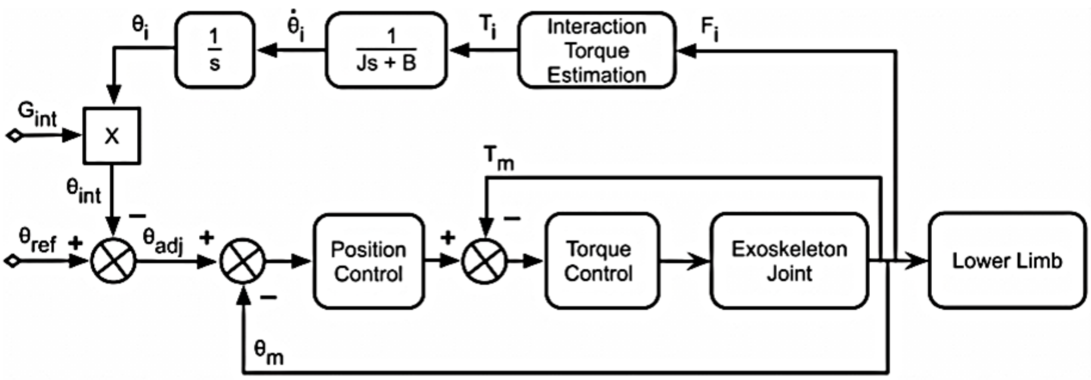

Figure 14. Control scheme for gait assistance of H2 robotic exoskeleton (67)

In (68), an adaptive gait control allows small forces to change the pre-defined path to facilitate compliance between the lower-limb exoskeleton and the subject (Figure **15**). It can also be implemented in Cartesian space, therefore, the inverse kinematics are not required (69–73).

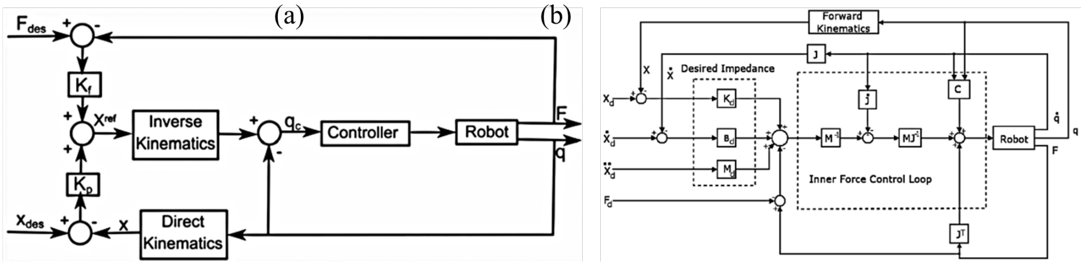

Figure 15. Schemes for force-based impedance controllers for Atlas exoskeleton. (a) Block diagram of the active-compliance controller (68), and (b) Internal force-based impedance control with position and force control loops (69,74)

The following assistance controllers reject the interaction torque to generate a compliant behavior: The research paper (75) explains the development of a control strategy to make the knee exoskeleton track the human lower limb, Figure **16**(a), where the control objective is the zero-force interaction between the human and the exoskeleton. The authors of this paper built the control scheme for a multidimensional lower limb exoskeleton, Figure **16**(b).

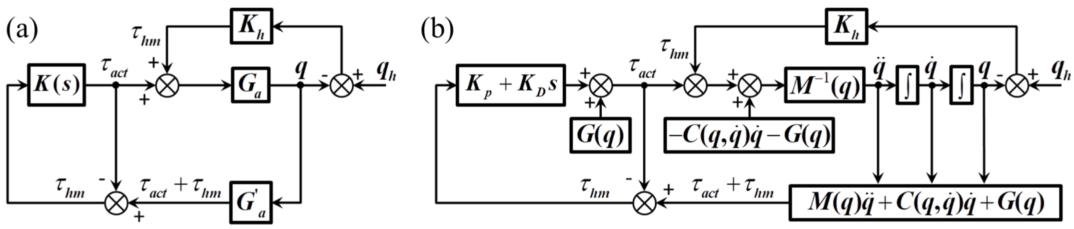

Figure 16. Assistance controller for a load-carrying lower limb exoskeleton. (a) control loop for single-degree system (75), and (b) control loop for multidimensional system (5)

The controller shown in (76) reduces the mechanical impedance of the joints of a lower limb exoskeleton, Figure **17**, and minimizes the interaction torque between the user's legs and the robotic exoskeleton. However, the authors of this submitted paper suggest that the user torque, T_{User}, must be added to the input control, T_U, because T_{User} is an acting signal.

Another control approach to assistance is human force augmentation, where the following works explain this type of controller: the authors in (77) and (78) used a sensitivity amplification control or the virtual torque control, $\tau_{act} = (1-\alpha^{-1})[M(\theta)\ddot{\theta} + C(\theta,\dot{\theta})\dot{\theta}] + G(\theta)$ (Figure **18**), which was implemented in the Berkeley Lower Extremity Exoskeleton (BLEEX) increasing the close-loop system sensitivity using measurements only from the exoskeleton and minimizing the joint torque exerted by the human when walking using the lower limb exoskeleton. Also,

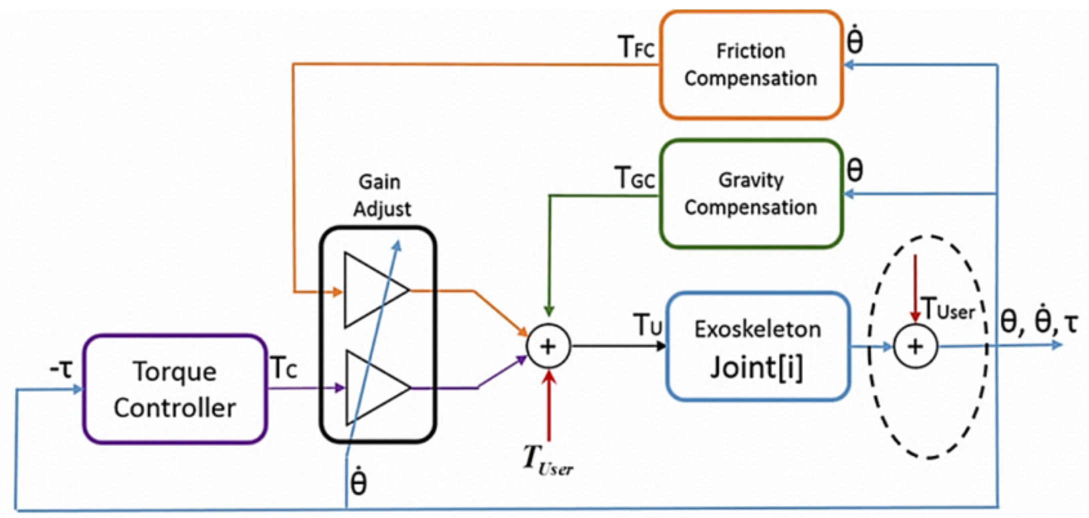

Figure 17. Controller for transparent mode in H2 lower limb exoskeleton (76)

the research in (79) employed an assistive device called the Wearable Walker lower-limb exoskeleton, designed to augment human capabilities through a blend control strategy (80), which is based on two separate Denavit-Hartenberg models, and generates smooth assistance torques that are blended to provide continuous and smooth overall assistance, such control prevents torque discontinuities during walking, enhancing transparency and reducing interaction pressures (81).

Adaptive control with an EMG-based assessment: EMG signals are used in rehabilitation assessment, as they provide information about muscle activity and the recovery of the patient's condition. Zhang *et al.* (82) proposed an nth-order nonlinear model to describe the relationship between surface EMG signals and lower limb joint angles.

The robot's impedance and assistive force should be adjusted based on the patient's muscular activity to enhance the human-robot interaction and adaptability. In early rehabilitation stages, low impedance facilitates ease of control, while in advanced stages, higher impedance increases interaction forces, keeping exercises challenging and motivating.

Human–Robot Synchronization

Current approaches to synchronizing human movement with robotic exoskeletons often require personalized adjustments to match each patient's unique walking patterns. This customization is necessary because individual gait characteristics vary significantly, making it difficult to apply a one-size-fits-all solution. However, this process is labor-intensive, as therapists must manually fine-tune the system based on patient feedback and visual observations, which can be

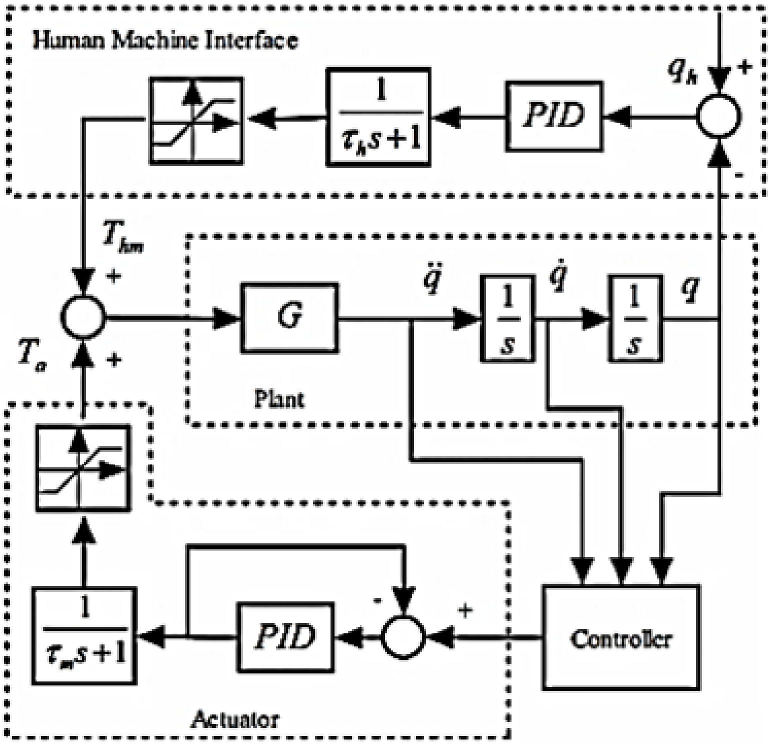

Figure 18. Block diagram of human-machine system with virtual torque control (8)

subjective and time-consuming. Automating this process by adapting the exoskeleton's parameters in real-time, based on factors like walking speed or the patient's movement intentions, could simplify its use and improve rehabilitation outcomes. Yet, both manual and automated offline adjustments may still fall short of optimizing the exoskeleton's performance. Real-time adaptive strategies that continuously adjust control parameters during therapy could improve effectiveness and reduce setup time.

Recent research (4) emphasizes the importance of advanced control strategies in human-robot synchronization. These strategies estimate the patient's movement state using deterministic or probabilistic methods, analyzing data such as joint angles, ground reaction forces, interaction forces between the human and robot, muscle activity, and even brain signals. Techniques like threshold-based algorithms, stochastic models, and adaptive oscillators are commonly employed. Effective synchronization is critical to maximizing the therapeutic benefits of exoskeletons, such as shortening the adaptation period and reducing energy expenditure during walking (83). To achieve this, the system must accurately interpret the user's movements and provide appropriate assistance or resistance, ensuring smooth coordination between the human and the robot.

An innovative approach to improving movement flexibility involves defining desired motions in terms of velocity rather than position. This method, known as Velocity Field Control (VFC), specifies a target velocity for each point in the workspace, effectively guiding the user along a predefined path (84). Unlike time-dependent methods, VFC allows for greater timing flexibility, as the reference velocity depends on position rather than time. However, this approach requires the controller to tolerate some tracking error. Studies reported in (85) and (86) explored VFC in fully back-drivable systems for overground walking training, using proportional velocity feedback. Low control gains can provide the Assist-as-Needed (AAN) property, whereas higher gains may reintroduce limitations similar to traditional VFC methods. Further research (86) and (87) has applied VFC to overground gait training systems, demonstrating its potential but also highlighting challenges in balancing control precision and flexibility.

A robust VFC method was proposed by (84), focusing on a lower-limb exoskeleton designed to follow circular trajectories. The authors in (88) introduced two control strategies that achieve the AAN property by monitoring velocity tracking errors. The first approach uses force measurements to adjust the robot's impedance, modulating a reference model based on tracking performance. This method employs a neural network to estimate system dynamics and does not require a back-drivable system. The second approach achieves the AAN property without force measurements by regulating control output based on tracking performance. While this method also uses a neural network to model system dynamics, it performs optimally in back-drivable systems.

Similarly, (89) proposed a spatiotemporal compliance control strategy for a novel wearable lower-limb rehabilitation robot (WLLRR). Compared to trajectory-based human-robot cooperation controllers (90, 91), the proposed strategy offers greater temporal flexibility and ensures passive behavior during physical interaction. Unlike traditional VFC methods (82, 88), this approach simplifies the encoding, generation, and adjustment of multi-joint movement tasks, providing both spatial and temporal compliance without relying on specialized back-drivable systems. The authors introduced performance metrics to assess motor variability and demonstrated that their control strategy enhances movement diversity while reducing interaction forces, guided by inter-joint coordination principles.

Presence of performance indicators in the analyzed studies

PIEs are essential for evaluating the effectiveness and quality of human–robot interaction in gait rehabilitation, as they provide key insights into biomechanical efficiency and functional outcomes despite the lack of full standardization across studies. Table 4 summarizes the estimated presence of PEIs in the 77 studies reviewed, linking commonly reported indicators (17) with representative commercial systems to support the assessment of robotic gait assistance strategies, where indicators are grouped into Goal-Level, Kinematics/Kinetics, and Human–Robot Interaction/Physiological categories and the percentages indicate their estimated frequency of use in the literature.

Table 4. Estimated presence of performance indicators in the n = 77 studies included in this review

Category	Performance indicator	Number of studies (n)	Estimated presence (%)	Commercial systems	Description / Typical use
Goal-Level	Minimum time / Maximum speed	24	31 %	Ekso GT, ReWalk, Indego	Evaluates training efficiency and mobility improvement
	Distance / Endurance	21	27 %	Ekso GT, ReWalk, Indego	Walking capacity, endurance and fatigue
	Stability	18	23 %	Lokomat, Ekso GT, ReWalk	Postural control and balance evaluation
	Versatility / Adaptability	14	18 %	Ekso GT, Keeogo, Indego	Assessment across different gait tasks
	Dependability / Reliability	9	12 %	Ekso GT, ReWalk	Consistency of performance over time
Kinematics / Kinetics	Spatiotemporal parameters (step length, cadence, gait speed, etc.)	52	68 %	Lokomat, Ekso GT, ReWalk, Indego, HAL	Core gait metrics
	Joint or limb kinematics (angles, ROM)	46	60 %	HAL, Ekso GT, ReWalk, Lokomat	Joint trajectory and angular displacement
	Joint or limb kinetics (torques, GRF, power)	40	52 %	Lokomat, Ekso GT, HAL	Mechanical load and power output
	Coordination	32	42 %	Lokomat, Ekso GT, Indego	Interlimb and human–robot coordination
	Symmetry	28	36 %	Lokomat, Ekso GT, ReWalk	Bilateral balance and gait pattern
HRI/ Physiological	Interaction forces	45	59 %	Ekso GT, ReWalk, Lokomat	Human–robot mechanical interaction
	Metabolic cost (VO_2, HR, calorimetry)	29	38 %	Lokomat, Ekso GT, ReWalk (in research trials)	Energy expenditure during walking
	Muscle effort (EMG)	40	52 %	HAL, Lokomat (research-integrated), Ekso GT	Muscle activation patterns, timing
	Comfort (subjective scales)	22	29 %	Ekso GT, ReWalk, Indego	User comfort, usability perception
	Ergonomics	17	22 %	Ekso GT, ReWalk, Keeogo	Fit, alignment, and anthropometric adaptation
	Safety (falls, adverse events, HR)	25	33 %	Lokomat, ReWalk, Ekso GT	Safety monitoring in clinical use
	Cognitive effort / workload	15	19 %	Lokomat, Ekso GT (research protocols)	Attention, stress, task load assessment

Discussion

The findings of this review provide a comprehensive overview of how control strategies for robot-assisted gait rehabilitation have evolved over time, moving from passive trajectory control approaches to more interactive, adaptive, and patient-centered control methods. Position-based trajectory control has historically played a fundamental role in early rehabilitation stages due to its simplicity and ability to ensure safe, repeatable movement patterns. However, its limited adaptability often restricts patient engagement and fails to fully exploit the patient's active contribution to gait retraining.

By contrast, hybrid and impedance-based control strategies have demonstrated improved human–robot interaction, enabling more natural joint dynamics and facilitating gradual patient participation. Bio-signal-based control methods, particularly those driven by electromyography (EMG) and other physiological signals, have opened new opportunities for intuitive interaction. Likewise, adaptive control approaches allow the modulation of robotic assistance according to each patient's motor abilities, enabling more personalized and responsive rehabilitation. A key insight emerging from these developments is the growing emphasis on human–robot synchronization, which has emerged as a crucial determinant of therapeutic effectiveness. Adaptive algorithms and biofeedback mechanisms allow real-time adjustments to assistance levels, improving motor relearning and overall patient outcomes.

A key aspect of the Assist-as-Needed (AAN) control is the ability to accurately assess and quantify the patient's participation level, degree of impairment, and rehabilitation progress. The AAN approach is deployed within most robotic systems because it is generating effectiveness in human gait rehabilitation. However, a persistent challenge in robotic rehabilitation is the accurate quantification of the true level of assistance provided by a robotic assistant as an exoskeleton when interacting with a patient with a disability. To provide partial assistance effectively, HRI must be measured or estimated to design a suitable control strategy that considers the human-applied torque. Literature reports several strategies that estimate these variables to modulate assistance and encourage active patient participation. To promote active patient engagement, the exoskeleton should engage users in tasks such as initiating steps, coordinating joint movements, and maintaining balance. This is accomplished by dynamically modulating the level of assistance or resistance in response to real-time biomechanical feedback during movement, ensuring optimal adaptation to the patient's needs.

Despite these promising advancements, several barriers continue to hinder large-scale clinical implementation. These challenges include the high cost of robotic devices, the need for specialized therapist training, the limited adaptability of control algorithms to heterogeneous patient profiles, and the variability in clinical protocols across rehabilitation centers. Furthermore, the integration of robotic systems into existing healthcare infrastructures requires regulatory approvals, maintenance resources, and clear evidence of cost-effectiveness. Overcoming these barriers is essential to ensure that robotic rehabilitation technologies can transition from controlled research settings to routine clinical and community-based practice, ultimately increasing patient accessibility and impact.

Another key challenge lies in translating engineering performance indicators (PEIs) into meaningful clinical outcomes, since metrics such as joint torques, interaction forces, and metabolic cost provide valuable insights into the mechanical efficiency of robotic devices but their true clinical value depends on their ability to reflect and predict improvements in patient mobility and independence. Evidence indicates that enhancements in spatiotemporal gait parameters, energy expenditure, and movement symmetry are often associated with gains in standardized clinical assessments. Based on the analysis of the reviewed studies, most works rely on spatiotemporal parameters, interaction forces, and joint kinematics as primary PEIs, reflecting a predominant focus on mechanical and kinematic measures rather than broader clinical dimensions.

Although PEIs quantify the mechanical and physiological interaction between the human and the robotic system, their clinical relevance emerges when they are directly correlated with functional outcomes. For example, reductions in metabolic cost, improved gait symmetry, and lower interaction forces have been linked to increased walking endurance, better balance, and greater patient comfort. These indicators can therefore serve as proxies for predicting functional gains such as higher walking speed, greater independence in daily activities, and reduced fatigue. Establishing strong links between PEIs and clinical scales—such as the Functional Ambulation Category (FAC), the 6-Minute Walk Test (6MWT), or the Berg Balance Scale—enables a more comprehensive assessment of rehabilitation effectiveness and supports evidence-based clinical decision-making. Furthermore, the distribution of PEIs observed in this review reveals a clear tendency to prioritize biomechanical efficiency indicators, which suggests an opportunity to strengthen their integration with standardized clinical outcomes, enhancing both their interpretability and clinical impact. Additionally, the authors of this paper suggest generating PEIs to assess both the gait quality performed by the human-exoskeleton system and the level of assistance provided by the exoskeleton.

Together, these findings highlight both the technological progress achieved in control strategies for robotic gait rehabilitation and the clinical translation challenges that remain to be addressed. Bridging the gap between engineering performance and functional outcomes, while removing implementation barriers, will be key to advancing the widespread clinical adoption of robotic rehabilitation technologies and maximizing their therapeutic impact.

In the context of robot-assisted gait rehabilitation, the selection of a control strategy involves balancing precision, adaptability, patient engagement, and clinical feasibility. The approaches analyzed in this review show diverse advantages and challenges depending on their design principles and intended application. To provide a clearer comparative perspective, Table 5 summarizes the control methods identified in the results section, highlighting their main advantages, limitations, and typical clinical or research applications. This synthesis facilitates the understanding of trade-offs between control accuracy and adaptability, and it supports evidence-based decisions when selecting or designing control strategies for rehabilitation systems.

Table 5. Comparative summary of control strategies in robot-assisted gait rehabilitation

Control method	Main advantages	Main limitations	Typical applications
Position-Based Trajectory Tracking	High precision and repeatability in predefined gait patterns. Simple implementation and low computational demand.	Limited adaptability to user variability. Low active engagement and minimal feedback from the patient.	Passive rehabilitation, early-stage training, trajectory guidance.
Force Control	Accurate regulation of interaction forces. Enables compliant human-robot interaction.	Sensitive to disturbances and sensor noise. Requires precise calibration and stable force feedback.	Assistive gait training with force regulation, cooperative control.
Impedance/Admittance Control	Flexible modulation of assistance levels. Closer approximation to human biomechanical behavior.	Nonlinear human dynamics increase control complexity. Requires proper parameter tuning for each patient.	Active-assisted rehabilitation, hybrid control schemes, perturbation-based training.
Hybrid Control (Position–Force)	Combines accuracy of position control with compliance of force/impedance control. Improves stability and comfort.	Higher complexity in controller design. Synchronization between control loops can be challenging.	Mid-to-late rehabilitation stages, active support with partial guidance.
Bio-Signal Driven Control (EMG/EEG/HR/RR)	Captures patient's voluntary intention in real time. Promotes active engagement and neuroplasticity.	High inter-subject variability and signal noise. Requires advanced signal processing and sensor reliability.	Personalized rehabilitation, brain–machine interfaces, adaptive assistance.
Adaptive Control	Real-time adjustment to patient performance and impairment level. Enhances human–robot synchronization.	High computational complexity. Requires robust algorithms and extensive validation.	Assist-as-Needed strategies, clinical settings with variable patient profiles.

Model-Based Control	High precision and predictability. Strong theoretical foundation for controller design.	Limited adaptability to uncertainties and nonlinearities. Depends on accurate dynamic models of the human–exoskeleton system.	High-performance robotic systems, pre-clinical testing, simulation environments.
Hierarchical Control	Modular structure allows for combining multiple control layers. Facilitates task prioritization and coordination.	Complex architecture and tuning. Higher computational and implementation costs.	Multi-task gait training, integration of multiple sensing modalities, research platforms.

An emerging research direction involves the use of data-driven control strategies to improve real-time adaptability and personalization in lower-limb exoskeletons. By leveraging large datasets and machine learning algorithms, these approaches can refine patient-specific assistance, optimize control parameters, and improve human–robot interaction dynamics (92–94).

Conclusions

This review provides a comprehensive framework for understanding assistance control in robot-assisted gait rehabilitation. It consolidates fundamental concepts and analyzes the most representative methods used in rehabilitation and locomotion robotics. The proposed taxonomy organizes control approaches into four key categories: (1) trajectory tracking based on position, (2) force/impedance control, (3) bio-signal-driven control, and (4) adaptive control, together with principles of human–robot synchronization. By structuring these strategies, the study clarifies their design trade-offs, clinical applicability, and potential impact on rehabilitation outcomes.

Research on rehabilitation and assistive robotic systems is highly extensive, encompassing areas such as control methods, human–machine interaction, biomechanics, sensor integration, and mechanical design. In this broad landscape, the originality of this work lies in providing a systematic and functionally oriented taxonomy that bridges control strategies and clinical rehabilitation goals, emphasizing the role of human–robot synchronization as a core design objective. Unlike previous reviews focused mainly on technical descriptions or device capabilities, this study integrates control principles with clinical performance indicators, offering a unified perspective for both engineers and rehabilitation specialists.

This synthesis serves as a reference framework for selecting and developing context-appropriate controllers, supporting both research and clinical practice. Furthermore, it highlights unresolved challenges related to controller adaptability, real-time response to patient variability, and the integration of intelligent, patient-specific control strategies. These insights are expected to guide future research and innovation, accelerating the translation of robot-assisted gait technologies from controlled environments into effective clinical applications.

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.

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Conflicts of interest

The authors declare that they have no competing interests.

Ethical implications

Not applicable

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References

[1] M. S. Alqahtani, G. Cooper, C. Diver, and P. J. Bártolo, "Exoskeletons for Lower Limb Applications: A Review," in *Bio-Materials and Prototyping Applications in Medicine*, Cham: Springer International Publishing, 2021, pp. 139–164. doi: https://doi.org/10.1007/978-3-030-35876-1_8

[2] S. González-Mejía and J. M. Ramírez-Scarpetta, "Advances in Robotic Rehabilitation for Lower Limb Recovery and Walking Assistance," *Ing. Compet.*, vol. 27, no. 1, pp. 1–24, Feb. 2025, doi: https://doi.org/10.25100/iyc.v27i1.14594

[3] M. A. Garcia Velarde, W. M. Alcocer Rosado, A. Blanco Ortega, A. Abúndez, C. Cortés, and J. Colin, "Lower limb assistance systems: A state of the art," *Lat. Am. Appl. Res. - Int. J.*, vol. 52, no. 2, pp. 89–99, Mar. 2022, doi: https://doi.org/10.52292/j.laar.2022.626

[4] J. de Miguel-Fernández, J. Lobo-Prat, E. Prinsen, J. M. Font-Llagunes, and L. Marchal-Crespo, "Control strategies used in lower limb exoskeletons for gait rehabilitation after brain injury: a systematic review and analysis of clinical effectiveness," *J. NeuroEngineering Rehabil.*, vol. 20, no. 1, p. 23, Feb. 2023, doi: https://doi.org/10.1186/s12984-023-01144-5

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

[6] A. R. Olaya, "Sistema robótico multimodal para análisis y estudios en biomecánica, movimiento humano y control neuromotor," Doctoral Thesis, Departamento de Ingeniería de Sistemas y Automática, Universidad Carlos III de Madrid, España, 2008.

[7] N. Hogan, "Impedance Control: An Approach to Manipulation: Part I, II, III," *J. Dyn. Syst. Meas. Control*, vol. 107, no. 1, pp. 1–7, Mar. 1985, doi: https://doi.org/10.1115/1.3140702

[8] A. Calanca, R. Muradore, and P. Fiorini, "A Review of Algorithms for Compliant Control of Stiff and Fixed-Compliance Robots," *IEEE/ASME Trans. Mechatron.*, vol. 21, no. 2, pp. 613–624, Apr. 2016, doi: https://doi.org/10.1109/TMECH.2015.2465849

[9] S. Oh, E. Baek, S. Song, S. Mohammed, D. Jeon, and K. Kong, "A generalized control framework of assistive controllers and its application to lower limb exoskeletons," *Robot. Auton. Syst.*, vol. 73, pp. 68–77, Nov. 2015, doi: https://doi.org/10.1016/j.robot.2014.10.001

[10] J. De Schutter, "A study of active compliant motion control methods for rigid manipulators based on a generic scheme," in *Proceedings. 1987 IEEE International Conference on Robotics and Automation*, Institute of Electrical and Electronics Engineers, 1987, pp. 1060–1065. doi: https://doi.org/10.1109/ROBOT.1987.1087856

[11] W. T. Townsend, "The effect of transmission design on force-controlled manipulator performance," Ph.D. Thesis, Massachusetts Institute of Technology, Dept. of Mechanical Engineering,United States, 1988

[12] T. Ishida and A. Takanishi, "A Robot Actuator Development With High Backdrivability," in *2006 IEEE Conference on Robotics, Automation and Mechatronics*, IEEE, Dec. 2006, pp. 1–6. doi: https://doi.org/10.1109/RAMECH.2006.252631

[13] K. Ohnishi, M. Shibata, and T. Murakami, "Motion control for advanced mechatronics," *IEEE/ASME Trans. Mechatron.*, vol. 1, no. 1, pp. 56–67, Mar. 1996, doi: https://doi.org/10.1109/3516.491410

[14] J. V. G. Robertson, N. Jarrassé, and A. Roby-Brami, "Rehabilitation robots: a compliment to virtual reality," *Schedae Press. Univ. Caen*, vol. 6, no. 1, pp. 77–94, 2010

[15] S. Pittaccio and S. Viscuso, "An EMG-Controlled SMA Device for the Rehabilitation of the Ankle Joint in Post-Acute Stroke," *J. Mater. Eng. Perform.*, vol. 20, no. 4–5, pp. 666–670, July 2011, doi: https://doi.org/10.1007/s11665-010-9826-7

[16] W. Meng, Q. Liu, Z. Zhou, Q. Ai, B. Sheng, and S. S. Xie, "Recent development of mechanisms and control strategies for robot-assisted lower limb rehabilitation," *Mechatronics*, vol. 31, pp. 132–145, Oct. 2015, doi: https://doi.org/10.1016/j.mechatronics.2015.04.005

[17] D. Pinto-Fernandez *et al.*, "Performance Evaluation of Lower Limb Exoskeletons: A Systematic Review," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 28, no. 7, pp. 1573–1583, July 2020, doi: https://doi.org/10.1109/TNSRE.2020.2989481

[18] C. Liang and T. Hsiao, "Walking Strategies and Performance Evaluation for Human-Exoskeleton Systems under Admittance Control," *Sensors*, vol. 20, no. 15, p. 4346, Aug. 2020, doi: https://doi.org/10.3390/s20154346

[19] W. Huo, S. Mohammed, J. C. Moreno, and Y. Amirat, "Lower Limb Wearable Robots for Assistance and Rehabilitation: A State of the Art," *IEEE Syst. J.*, vol. 10, no. 3, pp. 1068–1081, Sept. 2016, doi: https://doi.org/10.1109/JSYST.2014.2351491

[20] J. Cao, S. Q. Xie, R. Das, and G. L. Zhu, "Control strategies for effective robot assisted gait rehabilitation: The state of art and future prospects," *Med. Eng. Phys.*, vol. 36, no. 12, pp. 1555–1566, Dec. 2014, doi: https://doi.org/10.1016/j.medengphy.2014.08.005

[21] Z. Yang, W. Gu, J. Zhang, and L. Gui, *Force Control Theory and Method of Human Load Carrying Exoskeleton Suit*. Berlin, Heidelberg: Springer Berlin Heidelberg, 2017. doi: https://doi.org/10.1007/978-3-662-54144-9

[22] B. Chen *et al.*, "Recent developments and challenges of lower extremity exoskeletons," *J. Orthop. Transl.*, vol. 5, pp. 26–37, Apr. 2016, doi: https://doi.org/10.1016/j.jot.2015.09.007

[23] B. Chen, B. Zi, Z. Wang, L. Qin, and W.-H. Liao, "Knee exoskeletons for gait rehabilitation and human performance augmentation: A state-of-the-art," *Mech. Mach. Theory*, vol. 134, pp. 499–511, Apr. 2019, doi: https://doi.org/10.1016/j.mechmachtheory.2019.01.016

[24] P. K. Jamwal, S. Hussain, and S. Q. Xie, "Review on design and control aspects of ankle rehabilitation robots," *Disabil. Rehabil. Assist. Technol.*, vol. 10, no. 2, pp. 93–101, Mar. 2015, doi: https://doi.org/10.3109/17483107.2013.866986

[25] I. Tijjani, S. Kumar, and M. Boukheddimi, "A Survey on Design and Control of Lower Extremity Exoskeletons for Bipedal Walking," *Appl. Sci.*, vol. 12, no. 5, p. 2395, Feb. 2022, doi: https://doi.org/10.3390/app12052395

[26] V. Rajasekaran, "Adaptive Control for Wearable Robots in Human-Centered Rehabilitation Tasks," Doctoral thesis, Universitat Politécnica de Catalunya, BarcelonaTECH, España, 2015.

[27] O. Harib *et al.*, "Feedback Control of an Exoskeleton for Paraplegics: Toward Robustly Stable, Hands- Free Dynamic Walking," *IEEE Control Syst.*, vol. 38, no. 6, pp. 61–87, Dec. 2018, doi: https://doi.org/10.1109/MCS.2018.2866604

[28] H. Ma, W.-Y. Lai, W.-H. Liao, D. T.-P. Fong, K.-M. Chan, "Design and control of a powered knee orthosis for gait assistance," in **2013 IEEE/ASME International Conference on Advanced Intelligent Mechatronics**, IEEE, July 2013, pp. 816–821. doi: https://doi.org/10.1109/AIM.2013.6584194

[29] H. Vallery, E. H. F. van Asseldonk, M. Buss, and H. van der Kooij, "Reference Trajectory Generation for Rehabilitation Robots: Complementary Limb Motion Estimation," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 17, no. 1, pp. 23–30, Feb. 2009, doi: https://doi.org/10.1109/TNSRE.2008.2008278

[30] J. A. Saglia, N. G. Tsagarakis, J. S. Dai, and D. G. Caldwell, "Control Strategies for Patient-Assisted Training Using the Ankle Rehabilitation Robot (ARBOT)," *IEEE/ASME Trans. Mechatron.*, vol. 18, no. 6, pp. 1799–1808, Dec. 2013, doi: https://doi.org/10.1109/TMECH.2012.2214228

[31] K. Shamaei, P. C. Napolitano, and A. M. Dollar, "Design and Functional Evaluation of a Quasi-Passive Compliant Stance Control Knee–Ankle–Foot Orthosis," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 22, no. 2, pp. 258–268, Mar. 2014, doi: https://doi.org/10.1109/TNSRE.2014.2305664

[32] M. Cestari, D. Sanz-Merodio, J. C. Arevalo, and E. Garcia, "An Adjustable Compliant Joint for Lower- Limb Exoskeletons," *IEEE/ASME Trans. Mechatron.*, vol. 20, no. 2, pp. 889–898, Apr. 2015, doi: https://doi.org/10.1109/TMECH.2014.2324032

[33] P. Beyl, M. Van Damme, R. Van Ham, B. Vanderborght, and D. Lefeber, "Design and control of a lower limb exoskeleton for robot-assisted gait training," *Appl. Bionics Biomech.*, vol. 6, no. 2, pp. 229–243, July 2009, doi: https://doi.org/10.1080/11762320902784393

[34] I. Kardan and A. Akbarzadeh, "Output feedback assistive control of single-DOF SEA powered exoskeletons," *Ind. Robot Int. J.*, vol. 44, no. 3, pp. 275–287, May 2017, doi: https://doi.org/10.1108/IR-08-2016-0214

[35] I. Kardan and A. Akbarzadeh, "Robust output feedback assistive control of a compliantly actuated knee exoskeleton," *Robot. Auton. Syst.*, vol. 98, pp. 15–29, Dec. 2017, doi: https://doi.org/10.1016/j.robot.2017.09.006

[36] K. Anam and A. A. Al-Jumaily, "Active Exoskeleton Control Systems: State of the Art," *Procedia Eng.*, vol. 41, pp. 988–994, 2012, doi: https://doi.org/10.1016/j.proeng.2012.07.273

[37] M.-S. Ju, C.-C. K. Lin, D.-H. Lin, I.-S. Hwang, and S.-M. Chen, "A Rehabilitation Robot With Force-Position Hybrid Fuzzy Controller: Hybrid Fuzzy Control of Rehabilitation Robot," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 13, no. 3, pp. 349–358, Sept. 2005, doi: https://doi.org/10.1109/TNSRE.2005.847354

[38] M. Bernhardt, M. Frey, G. Colombo, and R. Riener, "Hybrid Force-Position Control Yields Cooperative Behaviour of the Rehabilitation Robot Lokomat," in *9th International Conference on Rehabilitation Robotics*, 2005. ICORR 2005., IEEE, 2005, pp. 536–539. doi: https://doi.org/10.1109/ICORR.2005.1501159

[39] G. Chen, P. Qi, Z. Guo, and H. Yu, "Mechanical design and evaluation of a compact portable knee–ankle–foot robot for gait rehabilitation," *Mech. Mach. Theory*, vol. 103, pp. 51–64, Sept. 2016, doi: https://doi.org/10.1016/j.mechmachtheory.2016.04.012

[40] P. Beyl *et al.*, "Safe and Compliant Guidance by a Powered Knee Exoskeleton for Robot-Assisted Rehabilitation of Gait," *Adv. Robot.*, vol. 25, no. 5, pp. 513–535, Jan. 2011, doi: https://doi.org/10.1163/016918611X558225

[41] G. Courtois, J. Chevrie, A. Dequidt, X. Bonnet, and P. Pudlo, "Design of a Rehabilitation Exoskeleton with Impedance Control: First Experiments," in *Proceedings of the 18th International Conference on Informatics in Control, Automation and Robotics*, SCITEPRESS - Science and Technology Publications, 2021, pp. 469–476. doi: https://doi.org/10.5220/0010580004690476

[42] A. Davoodi, M. Iranikhah, A. Ahmadi, A. Seyfarth, and M. A. Sharbafi, "Bioinspired Design and Control of BATEX, An Exosuit With Biarticular Compliant Actuators,"

IEEE/ASME Trans. Mechatron., vol. 29, no. 2, pp. 1352–1362, Apr. 2024, doi: https://doi.org/10.1109/TMECH.2023.3299117

[43] J. F. Veneman, R. Kruidhof, E. E. G. Hekman, R. Ekkelenkamp, E. H. F. Van Asseldonk, and H. van der Kooij, "Design and Evaluation of the LOPES Exoskeleton Robot for Interactive Gait Rehabilitation," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 15, no. 3, pp. 379–386, Sept. 2007, doi: https://doi.org/10.1109/TNSRE.2007.903919

[44] S. Hussain, S. Q. Xie, and P. K. Jamwal, "Adaptive Impedance Control of a Robotic Orthosis for Gait Rehabilitation," *IEEE Trans. Cybern.*, vol. 43, no. 3, pp. 1025–1034, June 2013, doi: https://doi.org/10.1109/TSMCB.2012.2222374

[45] B. Koopman, E. H. van Asseldonk, and H. van der Kooij, "Selective control of gait subtasks in robotic gait training: foot clearance support in stroke survivors with a powered exoskeleton," *J. NeuroEngineering Rehabil.*, vol. 10, no. 1, p. 3, 2013, doi: https://doi.org/10.1186/1743-0003-10-3

[46] K. K. Karunakaran, K. Abbruzzese, G. Androwis, and R. A. Foulds, "A Novel User Control for Lower Extremity Rehabilitation Exoskeletons," *Front. Robot. AI*, vol. 7, no. September, pp. 1–14, Sept. 2020, doi: https://doi.org/10.3389/frobt.2020.00108

[47] M. K. Shepherd and E. J. Rouse, "Design and Validation of a Torque-Controllable Knee Exoskeleton for Sit-to-Stand Assistance," *IEEE/ASME Trans. Mechatron.*, vol. 22, no. 4, pp. 1695–1704, Aug. 2017, doi: https://doi.org/10.1109/TMECH.2017.2704521

[48] J. E. Pratt, B. T. Krupp, C. J. Morse, and S. H. Collins, "The RoboKnee: an exoskeleton for enhancing strength and endurance during walking," in *IEEE International Conference on Robotics and Automation, 2004. Proceedings. ICRA '04. 2004*, IEEE, 2004, pp. 2430-2435 Vol.3. doi: https://doi.org/10.1109/ROBOT.2004.1307425

[49] C. Castellini, P. van der Smagt, G. Sandini, and G. Hirzinger, "Surface EMG for force control of mechanical hands," in *2008 IEEE International Conference on Robotics and Automation*, IEEE, May 2008, pp. 725–730. doi: https://doi.org/10.1109/ROBOT.2008.4543291

[50] B. Cesqui, P. Tropea, S. Micera, and H. Krebs, "EMG-based pattern recognition approach in post stroke robot-aided rehabilitation: a feasibility study," *J. NeuroEngineering Rehabil.*, vol. 10, no. 1, p. 75, 2013, doi: https://doi.org/10.1186/1743-0003-10-75

[51] O. Fukuda, T. Tsuji, M. Kaneko, and A. Otsuka, "A human-assisting manipulator teleoperated by EMG signals and arm motions," *IEEE Trans. Robot. Autom.*, vol. 19, no. 2, pp. 210–222, Apr. 2003, doi: https://doi.org/10.1109/TRA.2003.808873

[52] D. Maeda *et al.*, “Muscle synergy analysis of human adaptation to a variable-stiffness exoskeleton: Human walk with a knee exoskeleton with pneumatic artificial muscles,” in *2012 12th IEEE-RAS International Conference on Humanoid Robots (Humanoids 2012)*, IEEE, Nov. 2012, pp. 638–644. doi: https://doi.org/10.1109/HUMANOIDS.2012.6651587

[53] A. S. Kundu, O. Mazumder, R. Chattaraj, S. Bhaumik, and P. kumar Lenka, “Trajectory generation for myoelectrically controlled lower limb active knee exoskeleton,” in *2014 Seventh International Conference on Contemporary Computing (IC3)*, IEEE, Aug. 2014, pp. 230–235. doi: https://doi.org/10.1109/IC3.2014.6897178

[54] T. Lenzi, S. M. M. De Rossi, N. Vitiello, and M. C. Carrozza, “Intention-Based EMG Control for Powered Exoskeletons,” *IEEE Trans. Biomed. Eng.*, vol. 59, no. 8, pp. 2180–2190, Aug. 2012, doi: https://doi.org/10.1109/TBME.2012.2198821

[55] Y. H. Yin, Y. J. Fan, and L. D. Xu, “EMG and EPP-Integrated Human-Machine Interface Between the Paralyzed and Rehabilitation Exoskeleton,” *IEEE Trans. Inf. Technol. Biomed.*, vol. 16, no. 4, pp. 542– 549, July 2012, doi: https://doi.org/10.1109/TITB.2011.2178034

[56] Y. Fan and Y. Yin, “Active and Progressive Exoskeleton Rehabilitation Using Multisource Information Fusion From EMG and Force-Position EPP,” *IEEE Trans. Biomed. Eng.*, vol. 60, no. 12, pp. 3314–3321, Dec. 2013, doi: https://doi.org/10.1109/TBME.2013.2267741

[57] J. Charafeddine, S. Chevallier, S. Alfayad, M. Khalil, and D. Pradon, “Biokinematic Control Strategy for Rehabilitation Exoskeleton Based on User Intention,” *Int. J. Model. Optim.*, vol. 9, no. 6, pp. 322–328, Dec. 2019, doi: https://doi.org/10.7763/IJMO.2019.V9.730

[58] G. Kwakkel, B. J. Kollen, and H. I. Krebs, “Effects of Robot-Assisted Therapy on Upper Limb Recovery After Stroke: A Systematic Review,” *Neurorehabil. Neural Repair*, vol. 22, no. 2, pp. 111–121, Mar. 2008, doi: https://doi.org/10.1177/1545968307305457

[59] L. Marchal-Crespo and D. J. Reinkensmeyer, “Review of control strategies for robotic movement training after neurologic injury,” *J. NeuroEngineering Rehabil.*, vol. 6, no. 1, p. 20, Dec. 2009, doi: https://doi.org/10.1186/1743-0003-6-20

[60] S. Hussain, P. Jamwal, and M. Ghayesh, “Single joint robotic orthoses for gait rehabilitation: An educational technical review,” *J. Rehabil. Med.*, vol. 48, no. 4, pp. 333–338, 2016, doi: https://doi.org/10.2340/16501977-2073

[61] A. Duschau-Wicke, J. von Zitzewitz, A. Caprez, L. Lunenburger, and R. Riener, “Path Control: A Method for Patient-Cooperative Robot-Aided Gait Rehabilitation,” *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 18, no. 1, pp. 38–48, Feb. 2010, doi: https://doi.org/10.1109/TNSRE.2009.2033061

[62] B. M. Fleerkotte, B. Koopman, J. H. Buurke, E. H. F. van Asseldonk, H. van der Kooij, and J. S. Rietman, "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. NeuroEngineering Rehabil.*, vol. 11, no. 1, p. 26, 2014, doi: https://doi.org/10.1186/1743-0003-11-26

[63] E. T. Wolbrecht, V. Chan, D. J. Reinkensmeyer, and J. E. Bobrow, "Optimizing Compliant, Model-Based Robotic Assistance to Promote Neurorehabilitation," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 16, no. 3, pp. 286–297, June 2008, doi: https://doi.org/10.1109/TNSRE.2008.918389

[64] L. Chen, J. Huang, Y. Wang, S. Guo, M. Wang, and X. Guo, "Adaptive patient-cooperative compliant control of lower limb rehabilitation robot," *Biomim. Intell. Robot.*, vol. 4, no. 2, p. 100155, June 2024, doi: https://doi.org/10.1016/j.birob.2024.100155

[65] R. Riener, L. Lunenburger, S. Jezernik, M. Anderschitz, G. Colombo, and V. Dietz, "Patient-Cooperative Strategies for Robot-Aided Treadmill Training: First Experimental Results," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 13, no. 3, pp. 380–394, Sept. 2005, doi: https://doi.org/10.1109/TNSRE.2005.848628

[66] S. Jezernik, G. Colombo, and M. Morari, "Automatic Gait-Pattern Adaptation Algorithms for Rehabilitation With a 4-DOF Robotic Orthosis," *IEEE Trans. Robot. Autom.*, vol. 20, no. 3, pp. 574–582, June 2004, doi: https://doi.org/10.1109/TRA.2004.825515

[67] M. Bortole *et al.*, "The H2 robotic exoskeleton for gait rehabilitation after stroke: early findings from a clinical study," *J. NeuroEngineering Rehabil.*, vol. 12, no. 1, p. 54, Dec. 2015, doi: https://doi.org/10.1186/s12984-015-0048-y

[68] D. Sanz-Merodio, M. Cestari, J. C. Arevalo, X. A. Carrillo, and E. Garcia, "Generation and control of adaptive gaits in lower-limb exoskeletons for motion assistance," *Adv. Robot.*, vol. 28, no. 5, pp. 329–338, Mar. 2014, doi: https://doi.org/10.1080/01691864.2013.867284

[69] R. C. Bonitz and T. C. Hsia, "Internal force-based impedance control for cooperating manipulators," *IEEE Trans. Robot. Autom.*, vol. 12, no. 1, pp. 78–89, 1996, doi: https://doi.org/10.1109/70.481752

[70] Y. Mu, L. Zou, Z. Wang, J. Li, L. Jiang, and W. Wang, "A novel model predictive dynamic adaptive impedance control for robotic force tracking on complex surfaces," *Control Eng. Pract.*, vol. 163, p. 106398, Oct. 2025, doi: https://doi.org/10.1016/j.conengprac.2025.106398

[71] S. Haddadin and E. Shahriari, "Unified force-impedance control," *Int. J. Robot. Res.*, vol. 43, no. 13, pp. 2112–2141, Nov. 2024, doi: https://doi.org/10.1177/02783649241249194

[72] L. Gu and Q. Huang, "Adaptive Impedance Control for Force Tracking in Manipulators Based on Fractional-Order PID," *Appl. Sci.*, vol. 13, no. 18, p. 10267, Sept. 2023, doi: https://doi.org/10.3390/app131810267

[73] A. L. Jutinico, J. C. Jaimes, F. M. Escalante, J. C. Perez-Ibarra, M. H. Terra, and A. A. G. Siqueira, "Impedance Control for Robotic Rehabilitation: A Robust Markovian Approach," *Front. Neurorobotics*, vol. 11, Aug. 2017, doi: https://doi.org/10.3389/fnbot.2017.00043

[74] J. C. Arevalo and E. Garcia, "Impedance Control for Legged Robots: An Insight Into the Concepts Involved," *IEEE Trans. Syst. Man Cybern. Part C Appl. Rev.*, vol. 42, no. 6, pp. 1400–1411, Nov. 2012, doi: https://doi.org/10.1109/TSMCC.2012.2187190

[75] Y. Zhu, G. Zhang, C. Zhang, G. Liu, and J. Zhao, "Biomechanical modeling and load-carrying simulation of lower limb exoskeleton," *Biomed. Mater. Eng.*, vol. 26, no. s1, pp. S729–S738, Aug. 2015, doi: https://doi.org/10.3233/BME-151364

[76] R. Mendoza-Crespo, R. Soto, and J. L. Pons, "Transparent Mode for Lower Limb Exoskeleton," in *Wearable Robotics: Challenges and Trends, Biosystems & Biorobotics*, 2017, pp. 421–425. doi: https://doi.org/10.1007/978-3-319-46532-6_69

[77] R. Steger, Sung Hoon Kim, and H. Kazerooni, "Control scheme and networked control architecture for the Berkeley lower extremity exoskeleton (BLEEX)," in *Proceedings 2006 IEEE International Conference on Robotics and Automation, 2006. ICRA 2006.*, IEEE, 2006, pp. 3469–3476. doi: https://doi.org/10.1109/ROBOT.2006.1642232

[78] Xiuxia Yang, Zhang Yi, Zhiyong Yang, Lihua Gui, and Wenjin Gu, "Human-machine intelligent robot system control based on study algorithm," in *2008 IEEE International Conference on Industrial Technology*, IEEE, Apr. 2008, pp. 1–6. doi: https://doi.org/10.1109/ICIT.2008.4608502

[79] V. Lippi, A. Filippeschi, C. Camardella, F. Porcini, C. Maurer, and L. Lencioni, "EXOSMOOTH: Test of Innovative EXOskeleton Control for SMOOTH Assistance, With and Without Ankle Actuation," in **2022 17th ACM/IEEE International Conference on Human-Robot Interaction (HRI)**, IEEE, Mar. 2022, pp. 890–894. doi: https://doi.org/10.1109/HRI53351.2022.9889378

[80] C. Camardella, F. Porcini, A. Filippeschi, S. Marcheschi, M. Solazzi, and A. Frisoli, "Gait Phases Blended Control for Enhancing Transparency on Lower-Limb Exoskeletons," *IEEE Robot. Autom. Lett.*, vol. 6, no. 3, pp. 5453–5460, July 2021, doi: https://doi.org/10.1109/LRA.2021.3075368

[81] C. Camardella *et al.*, "User-Centered Evaluation of the Wearable Walker Lower Limb Exoskeleton; Preliminary Assessment Based on the Experience Protocol," *Sensors*, vol. 24, no. 16, p. 5358, Aug. 2024, doi: https://doi.org/10.3390/s24165358

[82] F. Zhang *et al.*, "sEMG-based continuous estimation of joint angles of human legs by using BP neural network," *Neurocomputing*, vol. 78, no. 1, pp. 139–148, Feb. 2012, doi: https://doi.org/10.1016/j.neucom.2011.05.033

[83] K. L. Poggensee and S. H. Collins, "How adaptation, training, and customization contribute to benefits from exoskeleton assistance," *Sci. Robot.*, vol. 6, no. 58, Sept. 2021, doi: https://doi.org/10.1126/scirobotics.abf1078

[84] H. J. Asl, T. Narikiyo, and M. Kawanishi, "An Assist-as-Needed Velocity Field Control Scheme for Rehabilitation Robots," in **2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)**, IEEE, Oct. 2018, pp. 3322–3327. doi: https://doi.org/10.1109/IROS.2018.8594244

[85] A. Martinez, B. Lawson, C. Durrough, and M. Goldfarb, "A Velocity-Field-Based Controller for Assisting Leg Movement During Walking With a Bilateral Hip and Knee Lower Limb Exoskeleton," *IEEE Trans. Robot.*, vol. 35, no. 2, pp. 307–316, Apr. 2019, doi: https://doi.org/10.1109/TRO.2018.2883819

[86] H. J. Asl, T. Narikiyo, and M. Kawanishi, "Neural network velocity field control of robotic exoskeletons with bounded input," in *2017 IEEE International Conference on Advanced Intelligent Mechatronics (AIM)*, IEEE, July 2017, pp. 1363–1368. doi: https://doi.org/10.1109/AIM.2017.8014208

[87] A. Martinez, B. Lawson, and M. Goldfarb, "A Velocity-Based Flow Field Control Approach for Reshaping Movement of Stroke-Impaired Individuals with a Lower-Limb Exoskeleton," in *2018 40th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, IEEE, July 2018, pp. 2797–2800. doi: https://doi.org/10.1109/EMBC.2018.8512807

[88] H. J. Asl, M. Yamashita, T. Narikiyo, and M. Kawanishi, "Field-Based Assist-as-Needed Control Schemes for Rehabilitation Robots," *IEEE/ASME Trans. Mechatron.*, vol. 25, no. 4, pp. 2100–2111, Aug. 2020, doi: https://doi.org/10.1109/TMECH.2020.2992090

[89] J. Zhou, H. Peng, S. Su, and R. Song, "Spatiotemporal Compliance Control for a Wearable Lower Limb Rehabilitation Robot," *IEEE Trans. Biomed. Eng.*, vol. 70, no. 6, pp. 1858–1868, June 2023, doi: https://doi.org/10.1109/TBME.2022.3230784

[90] D. P. Losey and M. K. O'Malley, "Trajectory Deformations From Physical Human–Robot Interaction," *IEEE Trans. Robot.*, vol. 34, no. 1, pp. 126–138, Feb. 2018, doi: https://doi.org/10.1109/TRO.2017.2765335

[91] J. Zhou, Z. Li, X. Li, X. Wang, and R. Song, "Human–Robot Cooperation Control Based on Trajectory Deformation Algorithm for a Lower Limb Rehabilitation Robot," *IEEE/ASME Trans. Mechatron.*, vol. 26, no. 6, pp. 3128–3138, Dec. 2021, doi: https://doi.org/10.1109/TMECH.2021.3053562

[92] F. Li, Y. He, J. Li, J. Ni, and X. Wu, "A data-driven shared control system for exoskeleton rehabilitation robot," in *2021 IEEE International Conference on Real-time Computing and Robotics (RCAR)*, IEEE, July 2021, pp. 899–904. doi: https://doi.org/10.1109/RCAR52367.2021.9517363

[93] Z. Peng *et al.*, "Data-Driven Optimal Assistance Control of a Lower Limb Exoskeleton for Hemiplegic Patients," *Front. Neurorobotics*, vol. 14, no. July, pp. 1–10, July 2020, doi: https://doi.org/10.3389/fnbot.2020.00037

[94] Z. Peng *et al.*, "Data-Driven Reinforcement Learning for Walking Assistance Control of a Lower Limb Exoskeleton with Hemiplegic Patients," in *2020 IEEE International Conference on Robotics and Automation (ICRA)*, IEEE, May 2020, pp. 9065–9071. doi: https://doi.org/10.1109/ICRA40945.2020.9197229