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Neuro-Mechanical Modeling and AI-Driven Exoskeleton Control for Rehabilitation Robotics: A Comprehensive Review

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Abstract

In recent years, rehabilitation robotics has become a promising area of research to enhance mobility and quality of life for people with neurological and musculoskeletal impairment. Lower-limb exoskeletons are one of the most promising advances in this field, combining advanced control strategies with principles from biomechanics to improve gait rehabilitation and functional recovery. This review discusses the state of the art in neuro-mechanical modeling approaches and Artificial Intelligence (AI) control techniques for rehabilitation exoskeletons. There are several important topics, such as musculoskeletal modelling, Central Pattern Generators (CPGs), neural control mechanisms, machine learning algorithms, reinforcement learning, sensor fusion and adaptive control strategies. Additionally, recent developments in the design of exoskeletons, in the field of actuators and in the human-robot interaction are provided. The review also covers the latest difficulties with models and their accuracy, real-time applicability, safety, personalization and clinical application. Last but not least, future research directions are proposed such as the incorporation of digital twins, sophisticated AI architectures and multimodal sensing devices, which can enhance rehabilitation results. The purpose of this review is to give the researcher and practitioner a structured overview of the state-of-the-art and future developments in Artificial Intelligence (AI)-assisted rehabilitation exoskeletons.

Keywords: Neuro-Mechanical Modeling; Bipedal Locomotion; Exoskeletons; Rehabilitation Robotics; Central Pattern Generators; AI Control; Gait Analysis

Introduction

Regular and symmetrical walking is the most common form of human locomotion, in which the two legs oscillate in a periodic and alternating manner [1]. In a step cycle, the legs perform three phases with different functions, including stance, swing, and transition. While the legs are performing periodic and parallel functions during walking, for each leg, the movement in the horizontal plane is completely controlled by simple rotations of the hip joint. Controlled hip stability, coordination, and actuation primarily determine the successful bipedal locomotion in a flat terrain without external disturbance [2].

However, balanced bipedal motion is a control problem of higher dimensionality, nonlinearity, and difficulty. During human locomotion motion, the kinetic and potential energies of lower extremities are transformed via the joint torques of the hip and knee using the visible coordinates of torso and legs [3]. It is possible to characterize the broad range of antiphase low-frequency patterns observed in bipedal gait, and to facilitate an understanding of how these patterns are created and selected by the control system. Since the ground surface is not planar, the vector of the position of the center of mass and the orientation of the torso varies with respect to time, which results in somatosensory feedback for control of bipedal locomotion [4].

To realize the above functionality, a hysteresis with a rate dependent stiffness was added in the torque input to the hip joints. The main objective was to reproduce less regular bipedal walking for like fast impulsive control of the hip joints or a high inertia for the angular velocity of the torso using a combination of the linear spring and damper [5]. Gait period, the horizontal and vertical positions of the center of mass, and the x, y, and z angles of the torso were examined to determine the dynamic responses of the internally modelled bipedal locomotion. During free gait, hip trajectories demonstrate that the input to the hip joints is affected by the change in walking speed, while the activation patterns of muscles in lower extremities remained similar across all speeds [6].

This article is organized in the form of a review but is not an original experimental study. Combines the latest advances in neuro-mechanical modelling, AI-based control, sensor fusion and rehabilitation exoskeleton design [7]. To showcase the existing state of the art, discuss different implementation strategies and explore the major challenges, as well as future research directions in the field of intelligent rehabilitation robotics. Although AI control and neuro-mechanical modelling have come a long way, there is still a need for systematic and thorough reviews that combine these two areas in rehabilitation exoskeletons [8].

Background and Literature Review

The increasing prevalence of traumatic brain injuries, strokes, and spinal cord injuries has caused many patients to suffer from lower-limb movements. Many patients are unable to walk, and standard rehabilitation devices cannot provide effective assistance [9]. Rehabilitation systems based on exoskeletons can effectively assist people with lower limb movement disorders, role-playing the function of the missing leg motor unit, and their detailed planning can provide rehabilitation training. The exoskeleton leg system can be seen as a walking robot, consisting of systems similar to human leg joints and actuated by engines, motors, or pneumatic cylinders. In recent years, extensive research has been conducted to create accurate neuro-mechanical models of biped after-pass plans based on musculoskeletal geometrical constraints for real human biomechanics [10]. The biped framework generally includes control methods, dynamics planners, and neuro-mechanical models. The biped neuro-mechanical simulation adds artificial neural networks to the physical engine to acquire limited knowledge-based control. This review discusses existing neuro-mechanical modeling approaches of biped, including simplified dimensional simulations from the element coordinate frame to the global ground frame, closed error directions, snapping to the equilibrium pitch angle, and statistical control inputs [11].

The neuro-mechanical control parameters of the biped model are trained and exported. Second, a musculotendon actuator model of the biped body is constructed [12]. For it, the neuromuscular transfer function and minimal excitation control are designed to generate high-fidelity input states. Finally, the trained simulated closed-loop imported angle and control inputs are applied to the real robotic bipeds for recovering. With the introduction of computational frameworks based on biomechanics, neuromuscular control and synthesis of muscle-actuated biped models become possible [13]. Muscles are modeled as nonlinear actuators with complex multi-segment dynamics, with emergent dynamics rendered by control inputs. The origin of controls has been approached from different perspectives, including motion capture from real humans or animals, but these typically require prior knowledge on the desired targeted tasks. Studies try to revise the control inputs by hierarchical optimization approach and genetic algorithms on locomotion dynamics render biomechanical plausibility, but these often get stuck in local minima [14]. A more principled model-driven approach cannot ensure the produced inputs accurately acquired this knowledge after converting simulation models to real systems, while performance can deteriorate even if the tuning rules are exactly the same [15].

Overview of bipedal locomotion

Bipedal locomotion is the primary form of mobility for humans and most terrestrial animals. However, it is also one of the most challenging forms of locomotion with non-linear dynamics, large degrees of freedom, and continuous contact switching between the anatomical limbs and the external ground [16]. With the strong development in new technologies, bipedal robot locomotion has made great progress and is one of the most successful products of intelligent robotic systems. However, it is also the greatest challenge for roboticist design and control. Multi-body dynamics models of bipedal locomotion have been widely built to investigate and improve locomotion robustness/stability [17]. These models can mimic animal or human walking cycles in explicit forms. Optimal control methods can use the derived/known model dynamical information to plan the future state or control input sequence [18].

The locomotion of bipedal systems is regarded as a hybrid dynamical system characterized by both continuous dynamics flowing in the state space and discrete dynamics switching among different state variables. It is an effective way to analyze the hybrid nonlinear locomotion systems using non-smooth analysis [19]. Various hybrid locomotion systems constructed with piecewise continuous smooth dynamics have been widely modeled and controlled with success. However, how to represent the hybrid locomotion systems over a uniform analysis tool is still an open and challenging problem [20].

As a braking damping effect emerges in the phase-rich locomotion systems, many technical difficulties arise when constructing and controlling their continuous-time models. A more universal non-smooth analysis method is developed to systematically study the phase-rich hybrid nonlinear systems with discontinuities in dynamical derivatives [21]. The developed method has been validated in multiple challenging scenarios, including 3D bipedal locomotion and aerial hopping. High-fidelity 3D musculoskeletal gait models with large degrees of freedom have been constructed to investigate bipedal locomotion control using actuated segments' joint torque with controllable parameters [22].

Existing exoskeleton technologies

Human gait rehabilitation is important to restore basic motor functions after lower limb injury and rehabilitation exoskeletons are recently designed for this purpose [23]. This review briefly introduces the existing rehabilitation exoskeleton technologies based on the mechanical design, actuation mechanism, Degree Of Freedom (DOF) configuration and control strategies. Existing bipedal rehabilitation exoskeletons are reviewed in terms of static mechanical design, actuation mechanism, DOF configurations and control strategies. Static mechanical properties of human locomotion are presented including contact point, joint angle and coordination for planar or 3D bipedal walking. The decoupled dynamic model of bipedal locomotion is summarized with polynomial approximation and FRF [24]. Passive exoskeletons are suitable for rehabilitation gait training with lower transferred weight and less power consumption. Rehabilitative lower extremity exoskeletons are predominantly used in stroke and incomplete SCI rehabilitation where the exoskeleton helps the user to stand and perform repetitive gait patterns which are initiated by the user [25]. The first working exoskeleton was designed as a power enhancing robot as part of DARPA to augment the performance of soldiers. The control mechanism sensed the movement of the user with single axis force sensors and would move the exoskeleton in the direction intended by the user. These systems, due to their complexity, need to make use of a variable body mass reduction mechanism to support the heavyweight of the robot on

Table 1: Summary of studies.

Study	Methodology	Device / Model	Key Results / Findings
Chandran *et al.,* 2023	Controlled experiments + subject-specific simulation	FDA-approved lower extremity exoskeleton	Exoskeletal-assisted locomotion showed improved gait symmetry and reduced metabolic cost compared to unassisted walking.
Tiseo *et al.,* 2018	Theoretical modeling of locomotion	Bipedal gait attractor model	Identified strange attractor dynamics in locomotion; implications for motor control and stability in robotic exoskeletons.
Zhang *et al.,* 2021	Computational modeling + simulation	Human knee exoskeleton	Developed models of assistive strategies; optimized torque assistance improved gait efficiency.
Karunakaran, 2016	Admittance control paradigm	Lower extremity exoskeleton	Proposed user-controlled admittance control; enhanced user adaptability and safety.
Manoonpong *et al.,* 2007	Neuronal control & learning in biped robots	Biped robot	Demonstrated adaptive fast walking; neuronal learning allowed real-time gait adjustment.
Yu *et al.,* 2021	Musculoskeletal modeling + humanoid control	Humanoid robots	Used human gait data to improve robotic gait; resulted in more natural movement.
Durandau *et al.,* 2021	Neuromechanical adaptive control	Bilateral ankle exoskeleton	Reduced joint torque & EMG activity across walking conditions; improved energy efficiency.
Zhang, de Silva, & Fu 2019	Sensor fusion survey	Assistive walking systems	Reviewed predictive control methods; highlighted benefits of environment-aware prosthesis control.
Chen *et al.,* 2022	Interactive information fusion	Lower limb exoskeleton	Developed gait recognition system; improved accuracy of movement classification.
Chen, Mu & Du, 2017	Biomechanical analysis	Human lower limb study	Provided joint angle/force data for exoskeleton design optimization.
Romero-Sánchez *et al.,* 2019	Theoretical modeling + muscle models	Hybrid orthoses	Designed cooperative actuation system; improved user comfort and efficiency.
Tucker *et al.,* 2020	GUI development + wearable robotics testing	Wireless control interface	Created open-source GUI for robotic control; increased accessibility and usability.
Alaa *et al.,* 2023	Dynamic modeling + control experiments	Leg prosthesis robot	Achieved accurate parameter estimation and stable control performance.

Table 2: Control in rehabilitation robotics.

Component	Description
Central Pattern Generators (CPGs)	Neural oscillators that generate rhythmic locomotion patterns without sensory feedback.
Sensory Feedback Loops	Incorporates proprioceptive and exteroceptive feedback to adjust gait in response to terrain or disturbances.
Musculoskeletal Dynamics	Mathematical model of human joints, muscles, and limbs that calculates torques, forces, and motion.
Exoskeleton Actuation	Robotic actuators that apply torque/force to assist or enhance joint movement according to control signals.
Controller	AI-based controller (e.g., reinforcement learning, model predictive control) that maps desired gait trajectories to actuator commands.
Optimization Module	Minimizes metabolic cost, joint stress, and fatigue while maintaining stability and gait symmetry.

top of the user. A pair of rigid links was attached to the leg of the user in front and behind the knee joints with a rotational spring attached at the knee joint [26]. This mechanism can be constructed in a spherical manner making pan-tilt possible as well. A variable ratio gear train mechanism was designed to reposition the cam at the hip joints of the exoskeleton. This movement can adjust the assistance timings with respect to the user's speed and therefore will aid to the natural behaviors of ambulation. The exoskeleton is lightweight and has lower power consumption compared to the conventional robotic mechanisms [27]. However, high cost in manufacturing still raises a practical roadblock. To overcome this issue, passive rehabilitation exoskeletons with smart elastic joints and bioinspired springs are proposed [28].

Neuroscience of gait and movement

There exist a large number of robotics research projects that have either very sophisticated adaptive algorithms but lack suitable mechatronic systems or possess very advanced mechatronic systems but relatively simple control algorithms. Systems with a proper combination of advanced robotics hardware and adaptive algorithms are rare [29]. Works on adaptive walking with real robot implementations can be found in 5 for bipeds. All these works are either too complex and thus not suitable for real applications or primarily focus on either the robotic system or the control algorithm. The main aim of this work is thus to combine sophisticated neuromechanical control and a realistic biomechanical simulator to study adaptive neuromechanical gait control during rapid bipedal locomotion [30].

In humans, reliable biped locomotion relies on dynamic balance in conjunction with stable gait behavior which are both achieved through bipedal gait control. In human bipedal walkers controlled via the Central Nervous System, the balance and gait outputs are robust and foldable. In rehabilitation robotics particularly robotic gait rehabilitation, the role of the balance and gait control in dynamic biped walking needs to be better understood to facilitate robotic gait rehabilitation device design; meanwhile new control schemes are required to achieve the balance and gait outputs for exoskeletons [31]. Determining how these outputs can be achieved is a key challenge which needs the development of realistic neuromechanical models of bipedal locomotion in which the balance and gait control should have a similar functional-structural architecture found in humans.

Recently, there has been an increasing interest in modeling and analyzing dynamic bipedal locomotion using a neuromechanical approach. Such simulations are normally referred to as musculoskeletal models, composed of mass-spring-damper biomechanical systems under neuromuscular control utilizing muscle model and neural control model. Musculoskeletal models may be driven to generate diverse dynamic gaits which can be tested for robustness and foldability [32] (Table 2).

Neuro-Mechanical Modeling Approaches

Modeling the human musculoskeletal system

The bone structure of the human body is modeled using OpenSim, which is a widely used tool for simulation, and the gait modeling of the humanoid robot is established using MATLAB. To acquire accurate motion, the OpenSim consumer is used to extract the generalized coordinates for motion analysis. Setup proper deformation visualization of the 3D model by calibrating the rotation and translation parameters of the camera visible to the OpenSim consumer and the coordinates of the 3D model on the Unity robot optimized in MATLAB. To quantitatively evaluate the accuracy of the prediction, the motion comparison between the real and prediction is analyzed, including angle position, angular velocity, and elbow torque. The bone models, including humerus, ulna, and Triangular Fibrocartilage Complex model (TFCC), are imported as STP files in a CAD tool. The collision surfaces of bone are defined in the CAD model to implement the contact detection for rigid body dynamics. The invisibility property of bones is set so that it can be completely hidden while rendering the model. The bone structure is animated based on the motion trajectory calculated from the OpenSim model. The TFCC is further converted into a mesh model for deformation with respect to the bone structures 6. The imported hierarchal model of OpenSim musculoskeletal simulation is represented as rigid body dynamics and collision detection [28]. The body components are connected using joints that define the appropriate degree of freedom for linkage dynamics. While rigid bodies remain unchanged, stationary frames are complemented by moving frames to model the geometry of links. And a flattened hierarchy of the OpenSim model is generated in Unity for real-time rendering and performance [33]. Existing OpenSim models usually pay little attention to mechanical properties. Rigid body links obtained from CAD tools may come with complex properties such as a large mass moment, thus increasing the modeling complexity. The finite mass of CGI methods approximates the rigid bodies numerically, which usually leads to rendered motion discrepancies and unexpected bounce events between links. With the rigged model composed of bones, the mass distribution of the links is simplified as a set of capsule shapes uniformly and easily loaded in the physics engine [34].

Neural control mechanisms

Adaptive, fast walking of biped locomotion can be achieved by using the feedback of mechanoreceptors as proprioceptive sensors in a simulated 6-DOF biped robot. The neural controller based on multi-layer feedforward neural networks consists of the sensory, hidden, and output layers. That is capable of generating walking gaits while these resonant circuits are capable of generating energetic patterns for fast walking gaits. Simulated biped robots are presented with a simplified sensor-driven control scheme for on-line gait generation, control, and adaptation. It can either use local feedback mechanisms or involve intermediate motor-neuron-like circuits. An additional high-level control for path following that is capable of computing simple steering commands is appended. Lateral stability had to be achieved, since during directed motion the active legs could not simply be blocked and the passive legs had to be driven with fixed motion patterns [35]. Human quadrupedal motions show that shoulder motions have to support turning maneuvers and changes in walking direction. The search for human-like motion patterns by optimization required a domain that did not impose specific kinematic properties. To a lesser extent this is also true for the bipedal domain.

The focus is solely on Gait Generation using a solution for forward projection. A generic and closed 3D mechanical model of a biped unit was designed as a tightly controlled inverse dynamic system. It consists of a spherical joint and seven active actuators at the joints (hip, knee, and ankle). The system was extended by an artificial neural network [36]. A multi-layer feedforward neural networks was adapted as a gait-generation neural controller. This network includes sensory and hidden layer neurons and motor neurons. The hidden neurons apply a Gaussian basis function, while the output neurons compute a weighted sum of the hidden neurons. Further, in more complex systems, the neural networks are likely to be recurrent. The neural network can generate walking gaits at ground tracks of different heights by modifying the weights of the connections between sensory and hidden layer neurons. Efforts can focus on high-level control issues to further improve the gait of the current bipedal robot simulator such as collision-free path planning, on-line obstacle avoidance, and control of force and compliance. They can be done using the same neural network architecture and learning methods but subject to different optimization criteria [37].

Integration of Neuro-Mechanical models

The neuro-mechanical musculoskeletal system of bipedal locomotion is modelled with the Hill-type linked actuators system, comprising a pair of hip, knee, and ankle joints, for the 3-D motion posture. To produce a synergistic joint motion of the locomotion, the action curves of the PD controllers are estimated from the swing motion of the hind leg joints. Since the PD-modeled joint motion of the hind leg does not include the ankle motion information of a fine stance posture, the Leg is independently expanded into the dimension of the knee joint PD control law, and tuned for the recovery limb gait transitions. Also, with the assistance of the implemented neural weights and delay of the E-protocol, the right leg controller of the swing leg locomotion is adapted with the essence of the postural adaption moment arm of the hidden state in the biped model. By controlling the desired action of the exoskeleton devices with the reference neural weights, the perturbation sequential updates are learned from the bio-inspired joint torque adaptation for the rising action of the exoskeleton ankle joint. And the indices from the conventional model-less adaptive control are implemented to comment on the validity and robustness of the comparing bio-inspired variable stiffness control strategy [38].

Through both neuromuscular model-based simulation and concurrent control of an exoskeleton, and by measuring biological signals and physiological states in real time, the proposed neuro-mechanical model-based control law is promising to adaptively assist a wide variety of movements. To promote the broad adoption of intelligent exoskeletons effectively, it is vital that control strategies are validated in the field, and thereby inspire further basic research and industrial implementation. Thus, the efforts will be on formulating robotic devices for both lab and non-lab settings. An application of an advanced exoskeleton device is discussed, including widely applicable and reconfigurable platforms open to all research teams around the world, as well as key enabling technologies that simultaneously address the urgent needs for the movement assistance industry and academic research in human-machine cooperation, emotion computing, and general robotics [39].

AI Techniques for Exoskeleton Control

The quest for AI-enhanced control paradigms for rehabilitation robotics and exoskeletons began in the late 1960s, when the first rehabilitation robot was developed. In the 1990s, robotic exoskeletons were developed. In the same decade, virtual reality exergames for rehabilitation use were introduced. Nowadays, sophisticated exoskeletons are widely used in clinical practice in Japan. In addition, many AI-enhanced commercial exoskeletons already exist. However, despite the above advances, there are still many challenges remaining to address [40].

Rehabilitation robotics and exoskeletons have largely been based on the model-based control paradigm and machine learning-based motion intent detection approaches. Yet the former calls for extensive engineering and modeling skills, while the latter is highly user-specific. As a result, the existing approaches have limited generalizability [41]. AI has recently emerged as a generalizable alternative. However, its applications to rehabilitation robotics and exoskeletons have lagged behind. On the contrary, rapid progress of AI has been made in other spinal cord injury-related applications, such as predicting recovery, virtual immersive reality, locomat systems, and functional electrical stimulation. It is surmised that many of these AI techniques can be readily adopted in rehabilitation robotics and exoskeletons, potentially precipitating fast advances. In short, there are compelling reasons to pursue AI-enhanced control paradigms for rehabilitation robotics and exoskeletons. Addressing these pressing needs can open up new business opportunities in research and development, manufacturing and testing, and marketing and commercialization [42].

Biomedical researchers need new generations of easy-to-use AI-enhanced rehabilitation robotics and exoskeletons to rapidly verify their research ideas. Control researchers need affordable and generic platforms to reproduce and benchmark their new ideas. This is a rapidly expanding and lucrative market. There are unprecedented opportunities for universities, companies and hospitals to further pursue new businesses. Yet there are also many challenges. AI-enhanced control paradigms need to be developed for rehabilitation robotics and exoskeletons. A few promising physical-model-based, data-driven, and modularization-based AI techniques have been reviewed. In addition, emerging technologies must be leveraged for efficient and effective rehabilitation robotics and exoskeleton design, testing and application. Due to time and manpower constraints, only a few of the AI-enhanced control paradigms and potential research directions were highlighted. Aiming for an exclusive research direction would both curb research creativity and slow down the development of the whole field. Possible alternative avenues for research have also been suggested, pursuing early converts and the continued interoperability between physical-model-based and data-driven approaches [43].

Machine learning algorithms

The two-class gait recognition and step counting classification algorithms were enhanced from pre-trained off-the-shelf models. Following that, hyperparameter tuning was performed using Gaussian random search. Hyperparameters include learning rate, batch size, dropout rate, regularizes, weight initializers, etc. In this case, using the hyperparameters tuned to the classification models and retraining accuracy decreased significantly. Since tailoring is needed on the basis of the latest results in the previous scenarios, a series of experimental studies were conducted to minimize trial-and-error settings in these cases. Batch size experiments showed that batch = 32 is the best choice using the others. Besides, two hyperparameter tuning techniques were applied in this experiment framework using selected categorical hyperparameter values: Random Search and Sequential Model-based Optimization. Random Search was able to achieve rewarding performances compared with the off-the-shelf models using only a portion of possible hyperparameter arrangements. In this research direction, efforts were made to explore the hyperparameter values of the classification models, and two learning rate decay mechanisms were either considered alone or combined with other techniques. Tests in a case study on real-time gait recognition also contain the investigation of such cases on augmented data in a new deep learning architecture. In the future, the application of unsupervised or semi-supervised transfer learning techniques may also improve the classification performance significantly. Permutation tests showed that the simulation data offered generalization ability. Performance degradation varies over states of a specific parameter: while a near-40% outperformance can be achieved at moderate and large values, performance deteriorated significantly when tested on the locomotion data simulated at low values. Thus, care needs to be taken when interpreting or generalizing simulator results, as the gap can vary over multiple dimensions [44].

Reinforcement learning for adaptation

Research efforts focused on developing adaptive control have the potential to enhance performance, robustness, and safety as robots enter physically interactive tasks. Reinforcement learning methods exhibit impressive capabilities for learning controllers, including adaptive manipulator controls, articulated body controls, and quadruped locomotion control. Safe RL has the potential to enable online adaptation of a robot's policy in real-world tasks, given the high potential for hazards in unknown environments, subsystem degradation, and other previously unforeseen circumstances [45].

Although scalable RL algorithms can learn policies that generalize well to unseen task variants, relatively little work has been done on how to enable autonomous adaptation of policies once deployed. Expecting re-training on previously unseen conditions is tantamount to anticipating a completely new task. Exploration during re-training on a new task is often highly inefficient, exposing the robot to potentially dangerous situations. Additionally, observations and reward functions may change with the new condition, complicating the learning process. In contrast, meta-learning or learning to learn is an abundant paradigm for rapid adaptation to new conditions after only a few time-steps. To mitigate adaptation failure, the ability to generalize or rapidly adapt an existing policy to cope with slight perturbations is critical. Meta-learning can also be used for adaptations that were previously unknown.

This work has proposed an integrated approach that builds on state-of-the-art model-based RL and meta-learning methods to produce an adaptable biped locomotion policy. After being trained in simulation on a range of terrain conditions, the learned controller was tested in hardware as well as simulated environments on previously unseen terrain variations. It successfully adapted online, achieving similar performance to the conditions it was trained on. The methods exhibited remarkable robustness to large unanticipated terrain variations, defying current expectations. Meta-learning was also shown to allow adaptation to previously unseen scaling variations, increasing the biped's stability [46].

Sensor fusion and data processing

Sensor fusion is a significant research area aimed at improving vehicle safety, autonomous driving capabilities, and human-robot interaction. As one of the most important methods to inform the decision-making system, it aims to more accurately perceive the current situation of the environment, thus creating a reliable system 8. With the improvement of sensors and the development of Artificial Intelligence (AI), multi-sensor fusion has achieved good results in many fields. However, the performance of a sensor might degrade due to aging, failure, and changes in operational environments. Not adapting the estimation system accordingly will significantly degrade the overall performance and, in a worst-case scenario, may also compromise safety. Therefore, fault detection and diagnosis, and timely sensor adjustment or replacement, is an important research area in effective sensor fusion. Highly integrated multi-sensor systems need to work in good cooperation. The integration framework, communication between sensors, and collaboration of field devices are hot issues. Fusion algorithms, especially nonlinear models at higher fusion levels, are also important but challenging [47].

The exoskeleton robot perception system obtains information from sensor inputs about the environment and user and transmits this information to the upper-level control system, as well as sharing global quantitative knowledge within safety constraints 9. The perception system of exoskeleton robots consists of a heterogeneous sensor package, context information fusion, and cognitive model-driven reasoning. A heterogeneous sensor package consists of various sensors in a similar or different modality that deliver information about the environment and human-robot interaction. Context information fusion is the process of transforming the representation of input information into a common semantic space. It integrates various local contexts into a global context. It can improve perception performance by mitigating outliers' influence through building interactions and connections between objects. A cognitive model of user intention is constructed based on a mathematical model, user inclination, and human motion inference. It is a knowledge-based estimation, which predicts future observations using existing information, including robot states, environment information, and user intentions. Then, the exoskeleton robot reasoning system selects a high-level control strategy based on a spatiotemporal model knowledge package [48].

Exoskeleton Design Principles and Technologies

The exoskeleton is composed of a series of mechanical components – rigid links and revolute joints that mimics the human anatomy as closely as possible. The overall structure of the exoskeleton is similar to a human waist down structure with the following elements: a structural frame including a pair of thighs, shanks, a pelvic brace, a torso brace, a waist strap, and a footplate. An electric actuator with a reduction gearbox is mounted on the frame to provide desired torque or joint assistive motion. A tension spring in series with the motor is implemented in the knee joint to prevent destabilization while standing up and sitting down. Here are the details of the exoskeleton system.

Components and Overview: Typical rehabilitation exoskeletons consist of a robotic frame with a waist attachment, knee and ankle joints, and a waist belt to pivotably attach the robotic frame to a user's pelvis. These components replicate a human skeletal structure with six actuated Degrees of Freedom (DoFs) about the robot-to-user connection, where a larger applied torque is required to perform a swinging motion using an actuated joint. Moreover, three unactuated DoFs – two passive revolute joints and a spherical joint – support in-plane motion control and allow ankle pitch and yaw rotations through passive means.

An actuator and an elastic element are embedded in each knee joint to ensure safety during motion execution and to compensate for motors' delay, respectively. The actuator is a brush-less DC motor with a maximum continuous torque of 12Nm. The gear ratio set to 30:1 provides a maximum output torque of 360Nm at the joint, which is designed to provide a similar assistive torque to a knee joint during standing up and sitting down tasks. A tension spring with a spring constant of 0.11Nm/rad is mounted in series with the motor, and with a pre-load angle of 15 degrees does not affect the motion during walking.

Modeling and Controller Design: The dynamics of an exoskeleton can be modeled as a lagged multi-body system with kinematic constraints and perturbation inputs, allowing exoskeleton control. The state-space model is developed to design a trajectory tracking controller using a linear state feedback controller for the reference angular trajectory of the knee joint, where tracking errors decay smoothly over time [49].

Mechanical design considerations

An exoskeleton can be seen as a bipedal mechanism and has three main abilities: robust and adaptive motion control, human-machine interaction estimation and adaptation, and safe and comfortable system design. The bipedal mechanism of exoskeletons is a highly nonlinear coupled multi-Degree Of Freedom (DOF) system that runs at different speeds and fluctuates under uncertain conditions. The robustness and adaptability of the AI-enhanced exoskeleton control mechanism depend on its motion models.

To simulate human bipedal locomotion, a human model with complex trunk-balance control may omit leg motion details. To design an AI-enhanced controller that can be used in different rehabilitation robots, the neuro-mechanical modeling of human bipedal locomotion with restraint simplification and GPSs is developed based on a simple biped model. Robotic assistors such as gait exoskeletons provide assistance as needed by unloading gait burden during rehabilitation. An interaction model consisting of a user and assistor is proposed to analyze the assistance strategies based on an upper body exoskeleton for rehabilitation [50].

Entering the bounce state is necessary for energy-efficient running. To underline the benefits of the bounce state, a simplified biped model with a stiff leg on a ground level is developed. Passive dynamics enhance gaits and stability in locomotion. Neural feedback drives and retuned parameters are needed for realizing stable gaits with hunting dynamics. Designing an assistive controller that applies assisting noise, rather than combative noise, based on a dynamic stochastic model could enhance the stability of bipedal locomotion and reduce human control effort. Non-cyclic landings are generated based on the natural bouncing dynamics of a simplified bipedal run.

Actuation systems

Various actuation approaches are used in exoskeleton devices. Active actuation is provided by a controlled motor and is typically used for robots and power expansion devices, while passive actuation is achieved through elastic compliant elements and is considered similar to human joints such as tendons and ligaments. Active exoskeleton devices controlling one or more Degrees of Freedom (DoF) have been designed to provide external motion control. Passive exoskeletons utilize elasticity that provides the actuation of exoskeletons through elastic compliant elements without motors,

Figure 1: AI-Enhanced exoskeleton control for bipedal locomotion in rehabilitation.

attempting to reduce the human metabolic cost during lifting tasks. investigated a passive ankle exoskeleton with differential gear devices during lifts. A physical device capable of tunable assistance of weight reduction in multiple human kinematics was developed. The physical system appears as a two-lumped element model with a torsional elastic spring and a frictional damper to account for the joint stiffness and damping. The size of a spring/gear is designed based on a slot-inspired design strategy combining lean methods and mechanical strength equations that follow lumped representations. It was confirmed in simulations that the proposed device compensates for total potential energy input at the ankle and knee joints [51].

User interface development

As digital devices increase in functionality and ubiquity, their interoperability is more critical than ever. A Graphical User Interface (GUI) is necessary between a developed robot and its end users to ensure that desired operations can be executed in a simple and intuitive way. Recent advances in wireless microcontroller technology enable cost-effective implementations of wireless and battery-powered robotics. These advancements allow rapid low-cost prototyping and development of research hardware. However, the availability of software is often a bottleneck. Therefore, hardware without software becomes a static and unusable asset. To mitigate this bottleneck, an open-source GUI for the Arduino Central Processing Unit (CPU) platform is presented. The GUI can facilitate rapid development of wireless operator interfaces for wearable robotics in an open-source framework [52].

This publication presents the design of a GUI for use with a wearable robotic exoskeleton for children with gait impairments. However, it is important to note that this GUI is compatible with any device that uses an Arduino compatible chip as the CPU. Beyond robotic devices, the GUI may be useful for other applications such as serial devices, wireless sensor networks, or any Arduino-based application with suitable data. The GUI has been validated to wirelessly operate robotic exoskeletons while simultaneously acquiring data from onboard sensors. This ability is crucial for the assessment of robotic devices, especially those used in rehabilitation. The GUI was specifically developed for wireless operation of a robotic device. However, the functions and tools included allow measurement, benchmarking, and logging of both on-board and external sensors, facilitating evaluation of any device compatible with the Arduino platform.

Recent advances in wireless microcontroller technology enable low-cost integration of this capability into robotic devices. However,

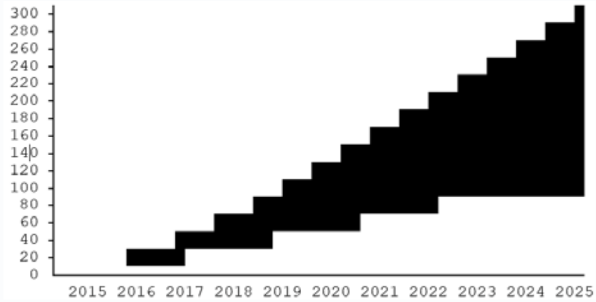

Figure 3: Annual growth of publications related to intelligent rehabilitation exoskeletons.

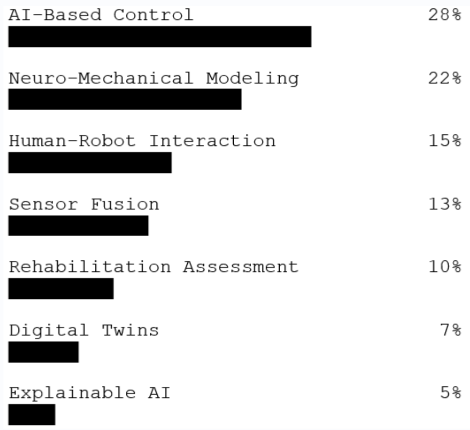

Figure 4: Distribution of major research themes.

in addition to powerful sensors and actuators, complex hardware requires sophisticated software. Therefore, a GUI is needed between the developed robot and its end users to ensure that desired operations can be executed in a simple and intuitive way.

Review Methodology

A thorough literature search of published work on neuro-mechanical modeling, artificial intelligence and rehabilitation exoskeleton technologies was done for this review. The major scientific databases such as Scopus, Web of Science, IEEE Xplore, ScienceDirect and Google Scholar were used to identify relevant studies.

A literature survey was conducted on papers from peer-reviewed journals, conference papers, and review papers published in the areas of rehabilitation robotics, biomechanical modelling, machine learning, reinforcement learning, sensor fusion, and human–robot interaction. Recent publications were given priority and seminal studies used to establish the foundations of the development of exoskeletons and neuro-mechanical control were taken into account. Selected studies were analyzed and classified based on their main objectives: musculoskeletal modeling, neural control mechanisms, AI based control strategies, exoskeleton design, sensor integration, and clinical rehabilitation use. The current achievement of AI-enhanced rehabilitation robotics, the limitation of the robotics technology, and future research opportunities were then analyzed with comparative analysis [53]. To provide a broader perspective on the evolution of intelligent rehabilitation exoskeleton research, a bibliometric-oriented analysis was performed [54]. The publication trends, research domains, AI techniques, global contributions, and emerging

Figure 5: Evolution of AI techniques used in rehabilitation exoskeletons.

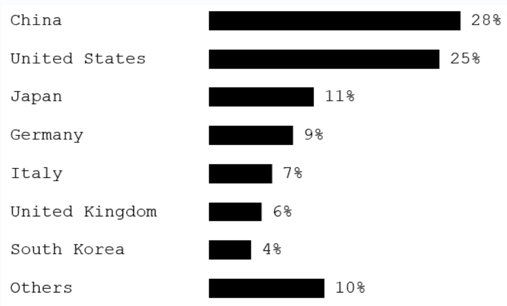

Figure 6: Country-wise contribution.

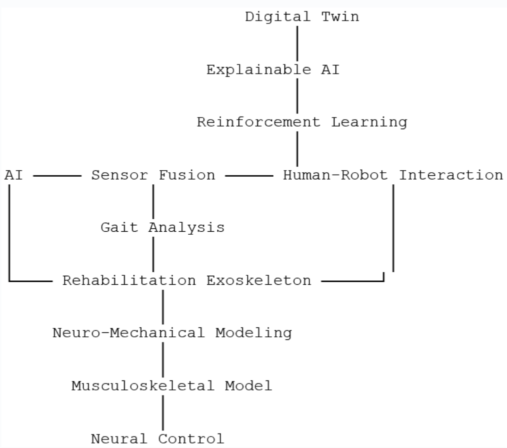

Figure 7: Keyword relationship network.

research directions are summarized in Figures 3-7 and Table 3.

Bibliometric analysis

Publication growth trend (2015-2025): The publication trend demonstrates a continuous increase in scientific interest in intelligent rehabilitation exoskeletons. The most significant growth occurred after 2020, coinciding with rapid advances in machine learning, wearable sensing technologies, and human-robot interaction research. The increasing number of publications reflects the transition of exoskeleton systems from laboratory prototypes toward clinically validated rehabilitation platforms. As shown in Figure 3, research activity has accelerated considerably after 2020, reflecting the rapid development of AI-enabled rehabilitation technologies.

Research domain distribution: Figure 4 illustrates the distribution of major research themes, highlighting AI-based control and neuro-mechanical modeling as the dominant research directions.

AI-based control systems represent the dominant research area, followed by neuro-mechanical modeling approaches. Recently, digital twins and explainable artificial intelligence have emerged as promising research topics due to their potential for personalized rehabilitation and transparent decision-making.

Evolution of AI methods: As presented in Figure 5, machine learning and deep learning remain the most frequently adopted AI techniques in rehabilitation exoskeleton research.

Machine learning remains the most frequently adopted computational approach due to its simplicity and proven effectiveness in gait classification and intent recognition. Deep learning techniques have experienced substantial growth owing to their ability to process complex multimodal signals such as EMG, EEG, IMU, and motion capture data. Reinforcement learning has become increasingly important because of its capability to generate adaptive and personalized assistance policies.

Global research contributions: The presented bibliometric trends are intended to provide a conceptual overview of the research landscape based on the reviewed literature and should not be interpreted as a formal scient metric analysis. Figure 6 summarizes the geographical distribution of scientific contributions in the field of intelligent rehabilitation exoskeletons.

China and the United States dominate the research landscape, together accounting for more than half of the total scientific output. Japan and several European countries continue to play significant roles, particularly in wearable robotics, biomechanics, and rehabilitation engineering.

Keyword co-occurrence network: The interrelationship among the most influential research topics is illustrated in Figure 7.

The emerging technologies expected to influence the next generation of rehabilitation exoskeletons are summarized in Table 3.

The bibliometric findings reveal a clear shift from traditional rule-based exoskeleton control strategies toward intelligent adaptive systems driven by artificial intelligence and neuro-mechanical modeling. Early research mainly focused on mechanical design

Table 3: Emerging research trends.

Emerging Technology	Expected Impact	Current Maturity
Digital Twins	Personalized rehabilitation planning	Medium
Explainable AI	Transparent clinical decision support	Low–Medium
Cloud Robotics	Remote rehabilitation services	Medium
Soft Robotics	Improved comfort and safety	Medium
Brain–Computer Interfaces	Direct neural intention decoding	Low
Multimodal Sensing	High-accuracy intent recognition	High
Reinforcement Learning	Personalized adaptive assistance	Medium
Human Digital Avatars	Real-time biomechanical prediction	Emerging

Table 4: Comparative findings from representative studies on AI-Enhanced rehabilitation exoskeletons.

Study	AI Technique	Exoskeleton Type	Main Findings
Chandran *et al.,* (2023)	Subject-specific simulation	Lower-limb exoskeleton	Improved gait symmetry and reduced metabolic cost
Durandau *et al.,* (2021)	Neuromechanical adaptive control	Bilateral ankle exoskeleton	Reduced joint torque and muscular effort
Chen *et al.,* (2022)	Information fusion algorithms	Lower-limb exoskeleton	Improved movement classification accuracy
Manoonpong *et al.,* (2007)	Neural learning control	Biped robot	Adaptive gait generation and real-time adjustment
Zhang *et al.,* (2021)	Computational modeling	Knee exoskeleton	Improved gait efficiency through optimized torque assistance

Table 5: Critical comparison of major neuro-mechanical and AI-based control approaches for rehabilitation exoskeletons.

Approach	Core principle	Main advantages	Key limitations	Suitable rehabilitation use	Clinical readiness
Central Pattern Generators (CPGs)	Generates rhythmic gait-like patterns using neural oscillator models inspired by the spinal cord.	Produces smooth and periodic locomotion; biologically inspired; suitable for repetitive gait training; can reduce the complexity of low-level gait generation.	Limited adaptability to sudden disturbances; requires careful tuning; may not fully represent impaired or asymmetric gait patterns.	Repetitive walking assistance, gait rhythm restoration, early-stage locomotion training.	Moderate
Musculoskeletal / Neuro-mechanical Modeling	Represents bones, joints, muscles, tendons, neural inputs, and joint torques to simulate human movement.	Provides physiological interpretation; supports torque estimation; useful for understanding human–robot interaction; improves personalization.	Computationally demanding; requires accurate anatomical and patient-specific data; difficult to validate clinically.	Patient-specific gait analysis, assist-as-needed control, simulation-based rehabilitation planning.	Moderate
Model Predictive Control (MPC)	Predicts future system behavior and optimizes control actions over a defined time horizon.	Handles constraints explicitly; suitable for balance and stability control; adaptable to changing gait phases; strong theoretical foundation.	High computational cost; requires accurate dynamic models; real-time implementation can be difficult for wearable systems.	Balance control, trajectory tracking, constrained joint assistance, safety-critical walking tasks.	Moderate to high
Machine Learning-Based Intent Recognition	Uses sensor data to classify user intention, gait phase, or movement pattern.	Improves recognition of walking, standing, turning, and stair movement; adaptable to user data; supports personalized assistance.	Requires large and representative datasets; may suffer from poor generalization; performance can decrease with sensor noise or user variability.	Gait phase detection, movement-mode recognition, user-intent prediction.	High for supervised classification tasks
Reinforcement Learning (RL)	Learns control policies through reward-based interaction with simulated or real environments.	Strong potential for adaptive and personalized control; can discover complex control strategies; useful for nonlinear and high-dimensional systems.	Safety concerns during exploration; simulation-to-reality gap; difficult reward design; limited clinical validation.	Adaptive assistance, personalized gait optimization, control under uncertain terrain or user conditions.	Low to moderate
Deep Learning	Extracts complex patterns from high-dimensional signals such as EMG, EEG, IMU, and motion capture data.	Handles nonlinear relationships; effective for large multimodal datasets; improves classification and prediction accuracy.	Requires extensive training data; low interpretability; risk of overfitting; may be sensitive to domain shifts between users.	EMG/EEG-based control, gait prediction, abnormal gait detection, sensor fusion.	Moderate
Sensor Fusion	Combines multiple sensors such as EMG, EEG, IMUs, force sensors, and vision systems.	Improves robustness and accuracy; reduces dependence on a single sensor; enhances user-intent recognition and environmental awareness.	Increases system complexity; requires synchronization and calibration; sensor failure can affect reliability.	Real-time gait monitoring, intention detection, terrain adaptation, safety enhancement.	High
Adaptive Control	Adjusts controller parameters online based on changes in user behavior, gait pattern, or environment.	Suitable for user-specific rehabilitation; improves robustness against variability; supports assist-as-needed strategies.	Stability proof can be challenging; may require continuous feedback; performance depends on sensor quality.	Personalized assistance, long-term rehabilitation, changing recovery stages.	Moderate to high
Impedance / Admittance Control	Regulates the mechanical interaction between the user and exoskeleton by controlling force–motion behavior.	Enhances comfort and safety; supports compliant human–robot interaction; widely used in assistive robotics.	Requires careful tuning; may not adapt sufficiently to complex gait abnormalities; limited prediction ability.	Safe joint assistance, compliant gait training, therapist-like interaction.	High
Hybrid AI–Neuro-mechanical Control	Combines physiological modeling with AI-based prediction, adaptation, and decision-making.	Integrates interpretability with adaptability; supports personalized and biologically informed control; promising for next-generation exoskeletons.	Complex implementation; requires multidisciplinary validation; limited standardized benchmarks; high computational demand.	Intelligent rehabilitation exoskeletons, adaptive gait assistance, patient-specific recovery programs.	Emerging but highly promising

Digital Twin-Based Control	Creates a real-time virtual representation of the patient–exoskeleton system for monitoring and prediction.	Enables predictive personalization; supports remote monitoring; can optimize rehabilitation plans; useful for safety assessment before real-world deployment.	Requires high-quality real-time data; computationally intensive; limited clinical adoption so far.	Personalized rehabilitation planning, remote rehabilitation, predictive maintenance and safety testing.	Emerging
Explainable AI (XAI)	Makes AI decisions more transparent and interpretable for clinicians, engineers, and users.	Improves clinical trust; supports safer decision-making; helps identify why a control action was selected.	Still technically immature in real-time robotics; explanations may be simplified or incomplete; difficult to standardize.	Clinical decision support, transparent adaptive control, safety-critical rehabilitation systems.	Emerging

and trajectory tracking, whereas contemporary studies increasingly emphasize adaptive learning, user-intent recognition, multimodal sensing, and personalized rehabilitation. The emergence of digital twins, explainable artificial intelligence, cloud-enabled rehabilitation platforms, and human digital avatars suggests that future exoskeleton systems will become more predictive, transparent, and patient-specific. These trends indicate a gradual convergence between biomechanics, neuroscience, robotics, and artificial intelligence, forming the foundation of next-generation rehabilitation technologies.

Comparative Analysis and Discussion

All the reviewed works show that the use of artificial intelligence techniques and the neuro-mechanical modeling in rehabilitation exoskeletons can make a significant contribution to their performance. MGAs, RLs and sensor-fusion strategies have demonstrated great promise in improving gait stability, lowering metabolic demand, improving gait classification, and providing adaptive assistance based on user-specific demands.

The literature suggests that AI-based control systems are superior to traditional rule-based control systems in adaptability, robustness, and personalization. There are still some difficulties in the real-time implementation and extension of the model, in the guarantee of safety, and in clinical verification. Such constraints still provide relevant research challenges to the next generation of intelligent rehabilitation systems. Representative findings from key studies reviewed in this work are summarized in Table 4. A detailed critical comparison of the major neuro-mechanical and AI-based control approaches is presented in Table 5.

As shown in Table 5, hybrid AI–neuro-mechanical approaches offer the most promising balance between physiological interpretability, adaptability, and personalized rehabilitation assistance. The comparative analysis suggests that there is no single control solution that can meet all of the needs of the field of rehabilitation exoskeletons. AI-based techniques offer improved adaptability and personalization, whereas classical control techniques like impedance control and MPC ensure stability and safety. The combination of these two approaches, known as sensor fusion, helps increase the reliability of the perception, while the neuro-mechanical modelling approach gives physiological interpretations. Hence, the most promising future path is the development of hybrid control architectures that integrate into a clinically validated framework biomechanical modeling, multimodal sensing, adaptive learning, and explainable decision making.

Performance metrics

To evaluate the performance of the reviewed frameworks, several performance metrics are considered from the user's perspectives and from the exoskeleton's perspectives. The performance metrics from the user's perspectives include stability, walking speed, distance, and energy consumption, whereas those from the exoskeleton's perspectives are command tracking, joint torque, joint velocity, and command delay performance metrics.

Comparison with Traditional Rehabilitation Methods

Among the various rehabilitation procedures for improving gait after stroke, the method in which therapists manually assist patients to walk, which requires manual support tools, is widely adopted. This method is necessary right after the stroke to lift the patients' body weights and to allow their bodies to stand upright, but it is noted that the Gait Recovery Training is more effective by the Capacitate Training. In the current Manual-Assisted Training procedure, therapists cannot always provide adequate assistance to their leaps since they need to concentrate on the co-ordination of the legs, hands, trunk and pelvis. Although these procedures require an enormous workload to the therapists, the exoskeleton technologies that have been developed by researchers in the past decades are only used in an experimental manner. Eventually, in order to minimize the labor by attending the Manual Assisted Training, a Portable Mobile Robot composed of a pelvic robot which confines the patient's pelvis, rib robot which confines the trunk, and administrator robot which assists leg movement for gait adaptation, was newly proposed. It is noted that the proposed system allows motions as free as possible without confining important joints such as knees or ankles for the patient while capably providing another assistance needed instead.

This concept and mechanism are applied to some gait adaptation robots which compensate natural motions of two degrees-of-freedom with high accuracy. The effectiveness of the system was shown in terms of its ability of gait adaptation and disturbance rejection. However, these robots are controlled solely by the predefined characteristics such as desired trajectories, joint torque and muscle dynamics, which are often considered a shortcoming of the traditional rehabilitation robots. Manual rehabilitation methods can adaptively manipulate the patient's condition by taking sufficient time and analyzing its motions, but the adaptability has been compromised in the gait adaptation robots while keeping high accuracy compensation. Another shortcoming is the difficulty to effectively assess the results of gait adaptation. Rehabilitation scientists need to analyze the experimental data afterwards analyzing inverse dynamics but no assessment is made during the training procedures. Thus, it is desired to apply an adaptive control method for gait rehabilitation with an attempt to utilize newly developed techniques in the field of pattern recognition or artificial intelligence techniques for this purpose.

User-Centered Considerations in Exoskeleton Design

User-centered design has become a critical aspect of rehabilitation exoskeleton development. Previous studies emphasize that comfort, usability, adaptability, safety, and ease of operation significantly influence user acceptance and long-term adherence to rehabilitation programs. Modern exoskeleton systems increasingly incorporate ergonomic design principles, intuitive user interfaces, and adaptive control strategies to enhance user experience and clinical effectiveness. Future developments should continue to prioritize human-centered design methodologies to ensure that technological advances translate into meaningful improvements in rehabilitation outcomes.

Challenges and Limitations

Several challenges must be overcome to exploit the full potential of simulation-IRL-based control frameworks. First, to identify a high-quality policy quickly, the simulator should be capable of reproducing the dynamics of exoskeleton-assisted locomotion faithfully. These aspects are very challenging due to the complexity of a biomechanical model featuring both exoskeleton and a human. The control strategy that coordinates human motions in a way that enables natural and stable movements is another interesting area of study that remains largely unexplored 1. The coordination between lower limbs is essential in bipedal locomotion, as gait patterns cannot be defined without defining motions in both legs. The development of sophisticated but few behavioral controllers is necessary to reproduce natural and versatile locomotion on top of biomechanical lower limbs with complex anatomical constraints and physical formats, such as contact stages and compliance. A compromise should be carefully made between these integration and anonymity challenges to ensure a timely delivery of the benefits of IPA to human gait control and further studies on the neural gymnastics underlying locomotion.

Next is a trade-off between symposium closures and increasing appetites. While a bipedal turning task can be simulated to enhance versatility in gait control with easily heightened realistic challenges, closing foot motions during bipedal locomotion renders specification of motion patterns very difficult. As one leg could take over extremities when the other leg glitches unexpectedly, foot rolling and crab motions may enhance energetic efficiency, as observed in humans. The study of turning control in bipedal locomotion should therefore be coupled with the design of a simpler bipedal foot model to be comprehended more easily and operated more quickly.

Finally, exploring the full potential of neuro-mechanical modelling is necessary. As recently demonstrated, neural controllers featuring neuromodulator control variables can achieve self-adjusting and dynamically balancing bipedal locomotion control even under the uncertainty of neuro-mechanical properties. Nevertheless, further adaptations on GTO variables customarily assumed constant in the modelling of neural controllers seem necessary to satisfy beyond stability robustness and increase the versatility of predictive locomotion control. A few challenging tasks for controlling an intense exploration of the gait patterns purely within the parameter space of neural controllers are also investigated 4.

Technical challenges

The application of necessary hardware, intelligent processing algorithms, and modeling approaches to bio-inspired robotics is paving the way for new technologies that can advance the fields of rehabilitation robotics and human-robot interaction. Novel neuromechanical models of various biological systems are being studied for possible use as bio-inspired representations of the lower-limb human dynamics, for example, to model the joint dynamics and/or the evolution of the model parameters over time. Bipedal locomotion can be described in a truly multi-physics way, taking into account the chrono physics of the gait generators, actuators, and foot-ground contact. While much progress has been made in the design of control algorithms for simulated bipedal robots, it is expected that extending and applying these methods to real robots will come with a host of new challenges.

The hardware and firmware of state-of-the-art humanoid robotics platforms are intrinsically heterogeneous systems with an increasing number of degrees of freedom and sensors. This necessitates engineered hardware and software systems that are potentially non-trivial to assemble and operate. The design and implementation of real-time performance-optimized communication protocols and control architectures are of utmost importance. The standardization of sensor integration interfaces and the creation of a framework for systematic benchmarking of performance and robustness would further accelerate the development of bipedal humanoids in terms of design generation, control parameter tuning, and further innovations in data-driven control methodologies.

Frontiers for the next generation of algorithms span a wide range, including solutions for complex biomechanical parameters identification problems, smooth and natural optimal bipedal locomotion synthesis in self-generated flat terrain, locomotion stabilization and control through push perturbations and uneven slopes, coordination and control of a network of physically coupled bipedal systems, and human-like adaptive human-robot interaction. Its goal is to review the current state of the art in robotic models of bipedal locomotion and address the pressing challenges that robot engineers, roboticists, and hidden system scientists will need to face in the coming years.

Ethical considerations

The increasing prevalence of assistive robotic exoskeletons will inevitably raise ethical, societal, and legal questions regarding their safe and beneficial use. Many human markets may benefit from exoskeletons, but the largest socio-economic impact is anticipated in the healthcare market. Subsequent studies are expected to improve the value, safety, and affordability of exoskeletons for rehabilitation and wider access across the world. However, along with all growth industries, exoskeletons raise ethical and societal questions. Societies and scientists will need to establish consensus on how to conduct assessments of the fundamental rights and freedoms for all concerned, including disabled patients, who may choose to use them. While individual countries may develop their own systems of taxonomies and standards over time, a universally negotiated system is preferred. Comprehensive review paper is expected to shed light on various aspects related to ethics and societal impact 1.

The rapid development of computer competitions, applicability for clinical use, and thoughtful interpretation of the data provided may generate enthusiasm for research in exoskeletons. To maximize the benefit of competitions, careful planning is required. Technological hurdles requiring robotic mechanisms to overcome complex terrain, reduce energy consumption, and enhance robustness must first be addressed. The procedure to robustly assess safety and efficacy must also be established so that both clinicians and scientists can develop design refinements based on systematic outcomes. In a new human market for rehabilitation robots, it is crucial to rationally commercialize clinically useful assistive robots and develop the most effective and applicable criteria for conducting comprehensive assessments of safety, efficacy, and comfort. Understanding how a robotic mechanism controls obstacle locomotion is vital for the design of assistive robots and control of functional locomotion assistance schemes.

Future research directions

The future of rehabilitation robotics research will see more intelligent, adaptive, and user-centric exoskeleton systems developed. Combining the knowledge of gait dynamics in combination with a more sophisticated artificial intelligence approach is a promising way to enhance gait rehabilitation, human–robot interaction, and personalized assistance strategies. The realization of digital twin technologies for rehabilitation exoskeletons is an important research direction. Digital twins can create virtual models of the user and robotic device that can be continuously monitored, analyzed, and controlled based on individual physiological and biomechanical data. Another interesting field of research is the use of multimodal sensing systems. The next generation of exoskeletons will integrate information gathered by an Electromyography (EMG) system, Electroencephalography (EEG) system, Inertial Measurement Units (IMUs), force sensors, and environmental perception systems. The integration can help to improve user-intent recognition, boost motion prediction accuracy, and facilitate safer and more responsive control strategies.

AI will remain a key factor in the development of rehabilitation exoskeletons. Adaptive decision-making capability is likely to be enhanced by reinforcement learning, deep learning, and transfer learning, while Explainable Artificial Intelligence (XAI) will boost system transparency and user confidence in autonomous rehabilitation systems. Personalized AI models that can tailor to individual patients' needs and recovery phases are a crucial area to explore in the future. There is also a need to further enhance the accuracy and physiological realism of neuro-mechanical models as part of future studies. More detailed musculoskeletal models, models of the neuromuscular systems, and models of central nervous system-inspired control architectures can help facilitate a better understanding of human locomotion and development of more effective rehabilitation strategies. Another challenge is the clinical validation. More extensive clinical trials across a wide range of patient groups are required to assess the long-term efficacy, safety, user-friendliness, and cost-effectiveness of AI-driven exoskeleton technologies. Standardized evaluation protocols and benchmarking frameworks will be crucial to compare various technologies and facilitate their adoption in clinical practice.

Last but not least, advancements in materials technology, soft robotics, wearable sensors, energy-efficient actuators, and cloud-based rehabilitation systems should be part of the next generation of rehabilitation exoskeletons. Such innovations can enhance user comfort, decrease device weight and power usage, and increase access to rehabilitation services in clinical and home setting. Overall, the convergence of neuro-mechanical modeling, artificial intelligence, advanced sensing technologies, and human-centered design is expected to drive the future evolution of rehabilitation robotics, leading to more effective, accessible, and personalized rehabilitation solutions.

Figure 8 illustrates the integrated relationship between physiological sensing, neuro-mechanical modeling, sensor fusion, artificial intelligence, adaptive control, and rehabilitation exoskeleton technologies. The framework highlights how multimodal data are transformed into intelligent control decisions that ultimately improve rehabilitation outcomes while supporting future developments such as digital twins, explainable AI, and personalized rehabilitation systems.

Conclusion

This review aimed to perform a thorough investigation of the neuro-mechanical modeling and artificial intelligence-based control strategies for rehabilitation exoskeletons. It is found that the synergies between musculoskeletal modelling, neural control mechanisms, machine learning algorithms, reinforcement learning and the fusion of multiple sensors have enhanced the efficiency of rehabilitation robotics and lower-limb exoskeleton systems. The analysis showed that the framework of the neuro-mechanical approach is useful for understanding human gait and assistive strategy development that allows for effective, adaptive gait stability and efficiency improvements

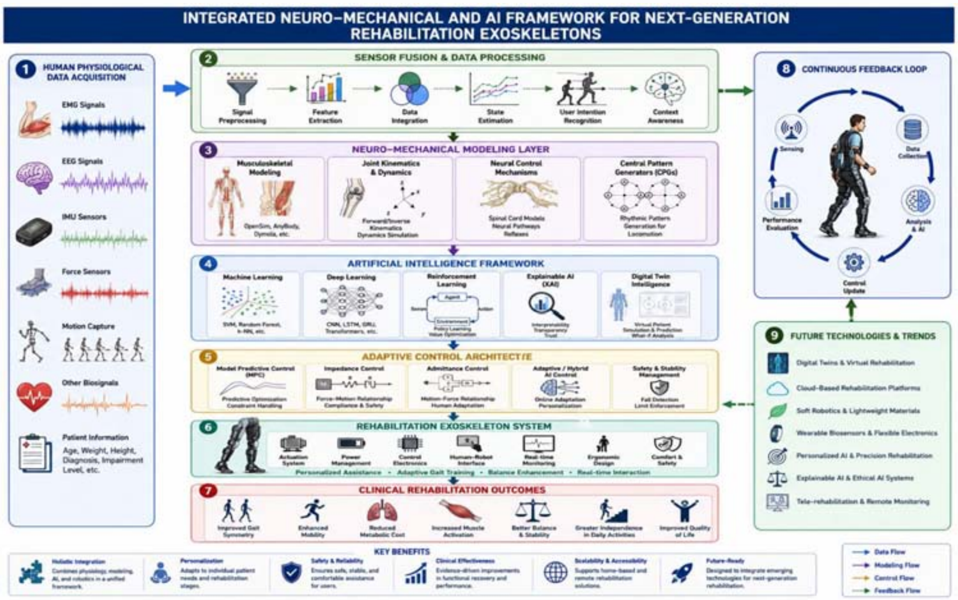

Figure 8: Integrated Neuro-Mechanical and AI Framework for Intelligent Rehabilitation Exoskeleton Systems.

and user-specific rehabilitation benefits. Moreover, recent advances in AI based control systems provide greater adaptability, personalization and robustness than traditional rule-based control systems.

However, there are still a number of challenges such as accurate biomechanical modelling, real-time implementation, safety assurance, clinical validation and the transferability of intelligent control systems to a range of users and rehabilitation scenarios. The challenges outlined above must be met if the advancement of exoskeleton technologies from the research laboratory to general clinical use is to be achieved. The adoption of digital twins, multimodal sensing systems, explainable AI, cloud-enabled computation, and individualized rehabilitation frameworks are likely to be the strength of the future developments. With these new technologies, the human–robot interaction will be better, rehabilitation will be optimized and next-generation smart rehabilitation exoskeletons will be developed much faster. In summary, neuro-mechanical modeling and AI control are pivotal technologies for the future of rehabilitation robotics and are likely to be increasingly vital in enhancing mobility, independence, and quality of life for people with neurological and musculoskeletal disabilities.

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