
Lower Limb Exoskeletons and Assistive Robotics: A Survey

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Abstract

Lower limb exoskeletons represent a significant advancement in assistive robotics, designed to enhance human mobility and adaptability, particularly for individuals with gait impairments. This survey paper provides a comprehensive overview of the current state and future directions of lower limb exoskeleton technology, with a focus on the integration of advanced technologies such as visual environment perception, motion pattern recognition, and human-machine cooperation. The development of sophisticated sensory systems, including RGB, event, LiDAR, and IMU data, has significantly enhanced the exoskeleton's ability to perceive and adapt to dynamic environments, ensuring user safety and stability. The implementation of reinforcement learning algorithms has further improved the adaptability and performance of exoskeletons in navigating diverse terrains, particularly in off-road conditions. Additionally, the development of advanced control methods, such as the Hierarchical Lyapunov-based Cascade Adaptive (HLCA) control, has been instrumental in refining cooperative control strategies, ensuring precise synchronization between the user and the exoskeleton's movements. The integration of physiological-based control strategies, such as electromyography (EMG) and electroencephalography (EEG), facilitates more intuitive and responsive interactions between the user and the exoskeleton, enhancing rehabilitation outcomes and user experience. Despite these advancements, challenges remain in optimizing the design and functionality of exoskeletons to ensure they are effective, comfortable, and practical for everyday use. Continued research and development in lightweight materials, advanced control systems, and sensory technologies are essential for advancing the field of assistive robotics and ensuring that lower limb exoskeletons can effectively support individuals with mobility impairments across diverse environments and applications. As research in this field continues to progress, it is expected that further advancements will be made, leading to even more innovative and effective solutions for individuals with mobility impairments. In conclusion, lower limb exoskeletons represent a significant advancement in assistive robotics, offering substantial benefits in enhancing human mobility and adaptability across diverse applications.

1 Introduction

1.1 Concept and Significance of Lower Limb Exoskeletons

Lower limb exoskeletons represent a significant advancement in assistive robotics, aimed at enhancing mobility and adaptability for individuals with gait impairments. These devices play a crucial role in rehabilitation and movement assistance, addressing the increasing need for effective solutions as the population of elderly and disabled individuals grows [1]. With the aging population facing challenges in performing Activities of Daily Living (ADLs) due to reduced mobility and strength, innovative support mechanisms are essential for promoting independence [2].

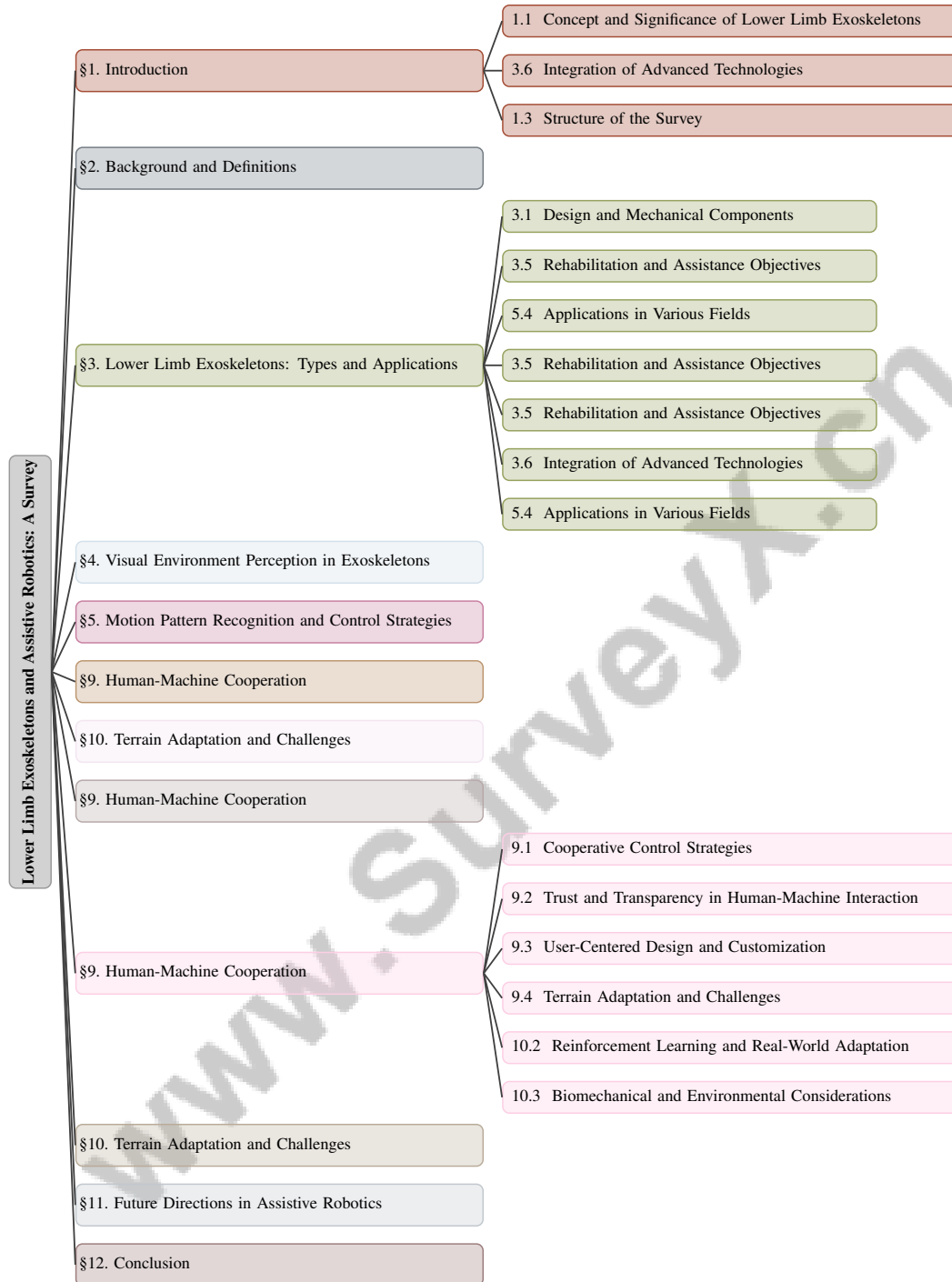


Figure 1: chapter structure

The evolution of exoskeletons, including soft wearable exosuits, focuses on improving human locomotion through impedance adaptation, enabling interaction with unpredictable dynamics and environments beyond controlled settings [3]. This development underscores the diverse applications of exoskeletons, enhancing mobility for both able-bodied individuals and those with motor impairments. The control of interaction forces between humans and exoskeletons is critical, significantly contributing to mobility enhancement and safety [4].

Effective locomotion over complex terrains necessitates the integration of advanced technologies within exoskeletons. This integration optimizes human-machine interaction, enhancing user experience and safety [5]. However, challenges remain in controlling lower-limb exoskeletons to alleviate body burden and improve motion performance, requiring innovative approaches for efficient human-robot collaboration [6].

Exoskeletons also show promise in neurorehabilitation, providing effective physical therapy and monitoring recovery [7]. Their potential to extend functional capabilities for individuals with mobility impairments is vital, bridging the gap between assistive robotics research and healthcare needs that hinder widespread adoption. Despite their promise, enhancing generalizability and adaptability across various tasks and user interactions remains a challenge [8].

Efforts to develop and validate modular sensor-based systems aim to address the limitations of current biomechanical assessment methods, which hinder the adoption and effectiveness of lower-limb exoskeletons in everyday use [9]. These exoskeletons are foundational in assistive robotics, providing substantial benefits in rehabilitation and movement assistance while improving the quality of life for individuals with mobility impairments. They serve not only as medical devices but also as assistive tools in industry and logistics, highlighting their broad societal impact. Addressing structural and technological limitations is essential for advancing the field and meeting diverse user needs across various applications.

1.2 Integration of Advanced Technologies

Integrating advanced technologies into lower limb exoskeletons is essential for enhancing adaptability and functionality in complex, dynamic environments. Key advancements include physiological-based control strategies, such as electromyography (EMG) and electroencephalography (EEG), which facilitate intuitive and responsive user interaction with exoskeletons [8]. These strategies allow real-time adaptation to user intentions, improving the effectiveness of rehabilitation and assistive applications.

The deployment of sophisticated sensory technologies, including a unique combination of RGB, event, LiDAR, and IMU data, significantly enhances the exoskeleton's environmental perception capabilities [5]. This comprehensive sensory input enables accurate terrain mapping and navigation, essential for maintaining stability and safety in varied environments. By addressing gaps in current datasets, these robust perception systems provide a holistic approach to environmental interaction.

Motion recognition technologies are pivotal for exoskeleton functionality. Advanced algorithms, such as the two-layered maximum entropy Markov model (MEMM), enhance the detection and recognition of human activities in unstructured environments [10]. This approach captures the hierarchical nature of human activities and adapts to task performance variations, crucial for personal assistive robotics.

Furthermore, the implementation of probabilistic models for human action recognition and corresponding movement generation underscores artificial intelligence's role in advancing exoskeleton technology. These models integrate natural language processing, computer vision, and machine learning techniques, enhancing usability and acceptance in various assistive applications. This integration improves system adaptability to users' nuanced needs while supporting offline functionality and reducing latency, promoting widespread adoption among individuals requiring mobility assistance [11, 12, 13, 2, 14].

Incorporating advanced technologies into lower limb exoskeletons significantly enhances their adaptability, efficiency, and overall user experience, facilitating applications in rehabilitation, mobility assistance for the elderly, and industrial settings. These innovations improve mechanical performance, reduce energy expenditure, and better simulate natural gait patterns while leveraging built-in sensors for continuous motor performance assessment, contributing to effective rehabilitation outcomes and user acceptance [15, 1, 16, 12]. Continued development and technology integration are vital for addressing diverse user needs and advancing assistive robotics.

1.3 Structure of the Survey

This survey is meticulously organized to provide a comprehensive overview of lower limb exoskeletons and their integration with advanced technologies. The paper is structured into several key sections, each focusing on specific aspects of exoskeleton development and application.

Section 1 introduces lower limb exoskeletons, detailing their significance in enhancing human mobility and adaptability. It discusses the integration of technologies such as visual environment perception and motion pattern recognition, setting the stage for subsequent sections.

Section 2 delves into background and definitions, providing a detailed explanation of core concepts like visual environment perception, motion pattern recognition, human-machine cooperation, and terrain adaptation. It reviews the evolution and current state of these technologies, establishing a foundation for understanding their application in exoskeletons.

In Section 3, the survey reviews various types of lower limb exoskeletons, highlighting their design, mechanical components, and objectives in rehabilitation and assistance. It explores applications across sectors such as healthcare and industry, emphasizing their societal impact, particularly in enhancing care quality for the elderly and individuals with disabilities, optimizing rehabilitation processes, and improving operational efficiency in manufacturing and agriculture. For example, advancements in assistive robotics support daily living activities, address caregiver shortages, and facilitate human-robot interaction for therapeutic purposes, while in industrial settings, robots are increasingly employed for tasks like assembly and quality control, transforming workforce dynamics and productivity [17, 18, 19, 13, 14].

Section 4 explores the role of visual sensors and perception technologies in enhancing exoskeleton adaptability to different environments. It tackles the complexities of terrain mapping and visual data processing by integrating advancements in visual perception technologies, specifically focusing on enhancing robotic locomotion capabilities. The development of a trajectory-based abstraction that combines model-free and model-based control layers enables robust, visually guided locomotion across diverse terrains. This approach improves the interaction between visual sensory data and control policies while addressing challenges in generalization from simulated environments to real-world applications, ultimately enhancing robotic systems' performance and adaptability in navigating complex landscapes [20, 14].

Section 5 provides an in-depth exploration of motion pattern recognition and control strategies for lower-limb exoskeletons, detailing algorithms and methodologies used to identify human motion patterns. It highlights control strategy classifications, including assistive control methods employing rule-based algorithms and trajectory-tracking techniques, crucial for optimizing user interaction and enhancing gait assistance effectiveness. Advanced machine learning approaches, such as boosted learning algorithms, improve action and movement recognition accuracy, contributing to the development of more responsive and adaptive exoskeleton systems [21, 22, 2, 23, 24]. The section reviews state-of-the-art control strategies, including model-based and learning-based approaches.

Section 6 delves into human-machine cooperation dynamics, focusing on cooperative control strategies that facilitate effective collaboration between humans and exoskeletons. It emphasizes the critical roles of trust and transparency in these interactions, highlighting how user-centered design principles can enhance overall experience and efficiency in human-robot teamwork. This analysis draws on contemporary research underscoring the importance of personalized interactions, which significantly improve user trust and comfort in assistive robotic systems [25, 26, 13].

Section 7 provides an in-depth analysis of challenges associated with adapting exoskeletons for various terrains. It reviews innovative solutions and strategies for terrain adaptation, including advanced techniques such as reinforcement learning, which facilitates adaptive learning from environmental feedback, and model predictive control, optimizing movement by anticipating future terrain conditions. The section highlights the importance of integrating visual sensory data with control policies to enhance exoskeleton performance across diverse and complex environments [23, 20].

Section 8 identifies promising research directions and technological advancements that could improve the effectiveness and acceptance of lower limb exoskeletons. The discussion encompasses anticipated advancements in visual environment perception, motion pattern recognition, and exoskeleton control, specifically highlighting the integration of machine learning frameworks for enhanced action and movement recognition, the potential of virtually worn robotic systems that alleviate mechanical constraints, and innovative uses of edge computing combined with natural language processing and computer vision to improve human-robot interaction. These developments aim to augment assistive technologies' capabilities, particularly for elderly individuals and those with disabilities, enhancing their autonomy and quality of life in smart living environments [27, 2, 14].

Section 9 synthesizes the main findings discussed throughout the paper, emphasizing the transformative potential of robotic technologies in healthcare. It addresses how advancements in robotics and artificial intelligence can alleviate caregiver shortages caused by an aging population, improve care quality for vulnerable groups such as the elderly and individuals with disabilities, and reshape societal interactions with healthcare systems. The section also highlights ongoing challenges that must be navigated to effectively integrate these technologies into everyday healthcare practices [17, 13]. This paper aims to provide a detailed and structured analysis of lower limb exoskeletons, offering insights into their current state and future directions. The following sections are organized as shown in Figure 1.

2 Background and Definitions

2.1 Core Concepts of Lower Limb Exoskeletons

Lower limb exoskeletons are underpinned by three essential components: visual environment perception, motion pattern recognition, and human-machine cooperation, which collectively enhance functionality and user experience for individuals with mobility impairments [23, 2, 16, 12]. Visual environment perception ensures stability and safety by enabling the detection and real-time 3D pose estimation of static and dynamic objects in complex terrains. Motion pattern recognition optimizes control schemes by aligning exoskeleton performance with natural human movements, crucial for rehabilitation where voluntary control engagement boosts neuroplasticity, especially in neurological impairment cases [28]. Hierarchical modeling aids in recognizing multiple actions related to Activities of Daily Living (ADLs), such as walking and transitioning between states.

Human-machine cooperation involves intent-based control strategies that interpret user commands, enhancing interaction during rehabilitation and daily activities. This cooperation is vital for controlling interaction forces and torques between the user and the exoskeleton, particularly during overground walking [8]. Modular sensor-based systems are being developed to evaluate and control exoskeletons outside laboratory settings, addressing significant methodological gaps [9].

These core concepts are integral to the design and functionality of lower limb exoskeletons, facilitating effective user interaction, adaptability to diverse terrains, and improved rehabilitation experiences for individuals with mobility impairments. They are crucial for optimizing mechanical design and control strategies, ensuring that exoskeletons provide necessary support while adapting to each user's unique needs [12, 29, 16, 23, 15]. The effectiveness of exoskeletons as assessment tools for measuring human motor performance further underscores their potential in rehabilitation and daily living contexts.

2.2 Evolution and Current State of Technologies

The evolution of lower limb exoskeletons is marked by significant technological advancements enhancing human mobility and adaptability. Initially designed for mechanical support mimicking human biomechanics, exoskeletons now integrate sophisticated technologies like visual environment perception and motion pattern recognition, significantly improving functionality and user experience [1]. Advanced visual environment perception technologies enable exoskeletons to navigate complex terrains with precision and safety through robust visual sensors [5]. Motion pattern recognition has progressed with learning-based algorithms facilitating real-time adaptation to human motion patterns [8]. However, achieving voluntary control over exoskeletons remains a challenge, limiting their full potential in rehabilitation and assistance, necessitating ongoing research into more intuitive control strategies [6].

Ensuring haptic transparency in interaction forces between humans and exoskeletons is a significant research focus, with efforts aimed at enhancing precision and reliability, crucial for user experience and safety [4]. Recent advancements have integrated cutting-edge technologies, significantly improving exoskeleton adaptability and efficiency in navigating complex terrains [5]. The transition from basic mechanical support to sophisticated assistive devices underscores the potential for exoskeletons to enhance mobility and independence for individuals with mobility impairments. Innovations in soft exoskeletons, rehabilitation robots, advanced control strategies, and mechanical designs promise to reduce energy expenditure by 10

3 Lower Limb Exoskeletons: Types and Applications

In the realm of lower limb exoskeletons, understanding their design and mechanical components is essential for comprehending how these devices enhance human mobility and functionality. This subsection delves into the intricate engineering behind exoskeletons, exploring the various mechanical elements that contribute to their effectiveness. By examining the interplay of actuators, sensors, and control systems, we can gain insights into the innovative technologies that facilitate human-like movement and support users in diverse applications.

3.1 Design and Mechanical Components

The design and mechanical components of lower limb exoskeletons are fundamental to their ability to enhance human mobility and perform effectively across various applications. These exoskeletons are meticulously engineered to replicate natural human movement while providing essential support, especially for individuals with physical disabilities or impairments [1]. The mechanical architecture of these devices typically comprises actuators, sensors, and control systems that operate in unison to facilitate human-like motion.

As illustrated in Figure 2, the hierarchical structure of lower limb exoskeleton design encompasses various elements, including mechanical architecture, control strategies, and their applications and advancements. This figure highlights the key components such as actuators and sensors, alongside strategies for sensory feedback and real-time adaptation, which are critical for the effective functioning of these devices.

A critical aspect of exoskeleton design is the integration of advanced control strategies that incorporate sensory feedback mechanisms, ensuring real-time adaptation to the user's movements and the surrounding environment. This adaptability is exemplified by the implementation of modular sensor-based systems that utilize inertial measurement units, force-sensitive resistors, and load cells for real-time biomechanical evaluation and control [9]. Such systems are pivotal in enhancing the functionality and comfort of exoskeletons, thereby promoting their widespread adoption.

The mechanical components of exoskeletons, such as actuators, play a vital role in facilitating movement. These components must be precisely engineered to provide the necessary support and flexibility for various activities, from walking to manual labor. For instance, the Chairless Chair by Noonee AG, designed for use in manual labor, exemplifies how exoskeletons can be integrated into everyday work environments to reduce strain and increase efficiency [1].

Advancements in sensor technology have also significantly contributed to the evolution of exoskeletons. Sensors provide real-time feedback on the user's movements and the surrounding environment, allowing the exoskeleton to adjust its operations accordingly. This real-time adaptability is crucial for ensuring user safety and comfort, particularly in dynamic and unpredictable environments [5].

The ongoing development of modular sensor-based systems aims to address the challenges associated with traditional biomechanical assessment methods, which are often inadequate and costly for everyday use in lower-limb exoskeletons [9]. These advancements are pivotal in improving the adaptability and user experience of exoskeletons, facilitating their integration into various applications such as manual labor, as demonstrated by the Chairless Chair from Noonee AG, which is designed specifically for use in manual labor environments [1].

3.2 Rehabilitation and Assistance Objectives

Lower limb exoskeletons play a pivotal role in rehabilitation and assistance by significantly enhancing the physical capabilities of individuals with mobility impairments. These devices are primarily designed to restore mobility, improve gait patterns, and enhance muscle strength, thereby facilitating rehabilitation and improving daily living activities. A critical goal in the rehabilitation context is to enable patients to actively contribute to their walking motion, which enhances engagement and the effectiveness of rehabilitation [28]. This is achieved through advanced control systems that allow for the dynamic adjustment of walking parameters, such as step length and stride time, in response to real-time user interactions [10].

The integration of cooperative control strategies in exoskeletons has been instrumental in enhancing rehabilitation outcomes. Such strategies enable a shared control paradigm where both the user

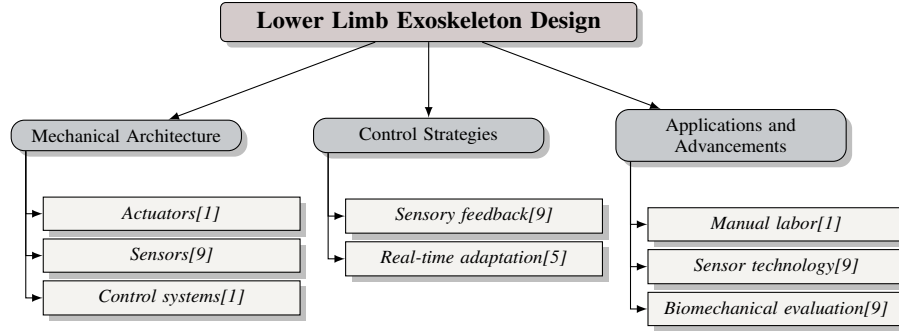


Figure 2: This figure illustrates the hierarchical structure of lower limb exoskeleton design, focusing on mechanical architecture, control strategies, and their applications and advancements. It highlights key components such as actuators, sensors, and control systems, alongside strategies for sensory feedback and real-time adaptation. The figure also emphasizes applications in manual labor and advancements in sensor technology and biomechanical evaluation.

and the exoskeleton contribute to the walking motion, thus fostering a more natural and effective rehabilitation process [30]. This cooperative approach is further supported by the development of assistive environments like the Assistive Gym, which serves as a benchmark for comparing control algorithms of robots interacting with humans and provides a framework for developing environments for various assistive tasks [31].

The implementation of voluntary control mechanisms in exoskeletons is crucial for effective rehabilitation, as it allows users to actively participate in their recovery process. This approach has been shown to enhance rehabilitation outcomes by promoting user engagement and motivation [28]. Additionally, the use of on-the-fly graph structure selection in motion recognition algorithms, such as those based on the Maximum Entropy Markov Model (MEMM), allows exoskeletons to dynamically adapt to different task speeds and styles, which is vital for achieving rehabilitation and assistance objectives [10].

Furthermore, the development of frameworks like Assistive Gym serves as a benchmark for comparing control algorithms and developing environments for various assistive tasks. These frameworks are essential for advancing the field of assistive robotics and ensuring that exoskeletons are effective and adaptable to diverse user needs [31]. Additionally, the use of cooperative control and intent-based approaches has been shown to enhance the rehabilitation process by enabling more personalized and adaptive human-robot training programs [7].

Despite these advancements, challenges remain in optimizing the design and functionality of exoskeletons to ensure they are effective, comfortable, and practical for everyday use. Ongoing research and development in lightweight materials and advanced control systems are crucial for significantly improving the functionality and performance of lower limb exoskeletons. These enhancements are particularly relevant in rehabilitation and assistance applications, where innovations such as soft exoskeletons can provide mechanical support, reduce energy expenditure by 10-20

3.3 Applications in Various Fields

Lower limb exoskeletons have found extensive applications across multiple fields, significantly impacting sectors such as healthcare, rehabilitation, and mobile robotics. In the medical field, exoskeletons, similar to those designed by companies like Kinova, are employed to assist individuals with mobility impairments, enabling them to regain independence and improve their quality of life. These devices facilitate rehabilitation by allowing users to engage in active movements, which is crucial for effective physical therapy and recovery [7].

The versatility of lower limb exoskeletons extends to various applications beyond healthcare, including industrial and logistics sectors, where they serve as assisting devices to enhance human performance and reduce physical strain. For instance, exoskeletons designed for mobile manipulation, as developed by companies like Kinova, are vital in environments where human-robot collaboration is necessary, such as in manufacturing and assembly lines. Revised Sentence: "These advanced exoskeleton

devices are designed to alleviate the physical strain on workers by enhancing their strength and endurance, thereby significantly improving productivity and safety in industrial environments, while also offering valuable data for assessing motor performance and reducing the risk of musculoskeletal disorders." [25, 22, 15, 32]

In the domain of rehabilitation, exoskeletons have proven to be effective tools for physical therapy, aiding in the recovery of individuals with mobility impairments. They offer a controlled environment for patients to practice movements and regain strength and mobility [7]. The integration of advanced sensory feedback and adaptive control mechanisms further enhances the functionality of exoskeletons, enabling them to provide personalized assistance tailored to the user's specific needs [8].

The mechanical components of lower limb exoskeletons are designed to mimic the natural movement of human limbs, providing support and assistance while ensuring user comfort and safety. These components often include actuators, sensors, and control systems that work in unison to facilitate natural movement and adapt to the user's intended actions. The development of advanced components in exoskeleton technology is essential for optimizing their functionality across a wide range of applications, including medical rehabilitation for individuals with motor impairments and industrial tasks that require enhanced physical capabilities. These components, which often incorporate built-in sensors, not only facilitate continuous monitoring of user performance metrics—such as range of motion, muscle strength, and gait parameters—but also play a critical role in ensuring the exoskeletons' effectiveness and reliability in both clinical and occupational settings. [12, 15]

3.4 Rehabilitation and Assistance Objectives

The primary objectives of lower limb exoskeletons in rehabilitation and assistance are to restore mobility, enhance physical capabilities, and improve the quality of life for individuals with mobility impairments. These devices are designed to assist individuals with walking difficulties, helping them regain independence and improve their quality of life [1]. Exoskeletons are particularly effective in rehabilitation settings, where they facilitate repetitive task training and promote neuroplasticity, which is crucial for recovery from neurological injuries such as stroke and spinal cord injuries [7].

In addition to rehabilitation, exoskeletons are also employed in various assistive applications, including aiding individuals with physical disabilities in performing Activities of Daily Living (ADLs) and enhancing the mobility of elderly individuals [2]. These devices help reduce the physical burden on users, thereby improving their quality of life and enabling greater independence.

The development of lower limb exoskeletons has been driven by the need to address the challenges faced by individuals with mobility impairments, such as difficulty in walking and maintaining balance. Exoskeletons offer a promising solution by providing the necessary support and assistance to enable these individuals to perform daily activities with greater ease and confidence [1]. The integration of advanced technologies, such as visual sensors and motion pattern recognition algorithms, enhances the adaptability and effectiveness of exoskeletons in diverse environments [5]. This integration not only aids in movement but also ensures the safety and stability of users, particularly when navigating complex terrains [3].

In rehabilitation, exoskeletons are used to assist patients in regaining their mobility and independence, offering a promising solution for individuals with physical disabilities [7]. The ability of exoskeletons to provide consistent and repetitive movement patterns is crucial for effective physical therapy, facilitating the recovery of motor functions and enhancing the quality of life for patients with mobility impairments.

The design of lower limb exoskeletons incorporates various mechanical components that are integral to their function. These include actuators, sensors, and control systems that work in harmony to provide the necessary support and assistance to the user [3]. The development of these components is crucial for optimizing the performance and adaptability of exoskeletons, enabling them to meet the diverse needs of users across different applications [9]. The role of visual perception technologies is also emphasized, as they play a critical role in the exoskeleton's ability to adapt to different environments and navigate complex terrains [5].

3.5 Rehabilitation and Assistance Objectives

Lower limb exoskeletons are primarily designed to assist individuals with mobility impairments, offering a significant impact in the field of rehabilitation and movement assistance. These devices are engineered to facilitate physical therapy by enabling repetitive task training, which is essential for neuroplasticity and recovery in patients with motor impairments [7]. The goal is to engage patients in active participation, promoting motor learning and enhancing their functional capabilities [8].

In rehabilitation settings, exoskeletons are employed to support gait training for individuals with neurological conditions such as spinal cord injuries, stroke, and other mobility impairments [6]. They provide consistent and controlled assistance, allowing patients to perform movements that would otherwise be challenging or impossible. This not only aids in physical recovery but also supports psychological well-being by fostering a sense of independence and self-efficacy [7].

In addition to rehabilitation, lower limb exoskeletons have found applications in various fields, including industrial settings where they assist workers in performing physically demanding tasks, such as lifting and carrying heavy loads, thereby reducing the risk of musculoskeletal injuries [2]. The versatility and adaptability of exoskeletons make them suitable for diverse applications, from facilitating mobility for individuals with disabilities to enhancing the physical capabilities of workers in industrial environments. As such, they hold significant potential to transform industries and improve quality of life across different sectors.

3.6 Integration of Advanced Technologies

The integration of advanced technologies such as visual environment perception and motion pattern recognition is pivotal in enhancing the functionality and adaptability of lower limb exoskeletons. Visual environment perception enables exoskeletons to interpret and respond to dynamic surroundings, thereby facilitating safe and efficient navigation across various terrains [5]. Advanced sensor technologies, including LiDAR, cameras, and depth sensors, provide critical data that allows exoskeletons to construct a comprehensive model of the environment, enabling them to anticipate and adapt to changes in terrain and obstacles [3].

Motion pattern recognition is another critical technology integrated into lower limb exoskeletons, allowing for the identification and adaptation to human gait patterns. This capability is essential for optimizing control strategies and ensuring that the exoskeleton's movements are synchronized with the user's natural gait, thereby enhancing comfort and effectiveness in rehabilitation and assistance applications [28]. Techniques such as machine learning algorithms and probabilistic models are employed to achieve real-time adaptation to the user's movements, improving the exoskeleton's performance in dynamic environments.

Human-machine cooperation is another critical area of focus in the integration of advanced technologies into lower limb exoskeletons. Intent-based control strategies are employed to facilitate seamless interaction between the user and the exoskeleton, allowing for a more intuitive and responsive experience [8]. These strategies are crucial for optimizing the performance of exoskeletons in both rehabilitation and assistive applications, ensuring that they can effectively support users in their daily activities [7].

The integration of these advanced technologies into lower limb exoskeletons represents a significant advancement in the field of assistive robotics. By enhancing the adaptability, efficiency, and user experience of these devices, researchers are paving the way for their broader application across various fields. As advancements in lower limb exoskeleton technology continue to accelerate, these devices are anticipated to significantly enhance human mobility and adaptability across a wide range of environments and applications. Specifically, lower limb exoskeletons are being developed with dual objectives: facilitating rehabilitation for individuals with mobility impairments and augmenting the physical capabilities of workers in demanding job settings. Innovations in actuator placement and the incorporation of compliant mechanisms are improving the functionality and comfort of these systems, thereby enabling users to experience reduced energy expenditure during movement. This evolution positions lower limb exoskeletons as vital tools not only in healthcare and rehabilitation but also in industrial applications, ultimately contributing to increased independence and quality of life for users. [22, 16, 12]

3.7 Applications in Various Fields

Lower limb exoskeletons have emerged as versatile tools with diverse applications across multiple sectors, significantly enhancing human mobility and performance. In the medical field, these devices are employed to assist individuals with mobility impairments, aiding in rehabilitation and improving patients' quality of life by enabling them to regain independence and perform Activities of Daily Living (ADLs). Furthermore, exoskeletons have been instrumental in rehabilitation, facilitating physical therapy by providing consistent and controlled assistance during repetitive task training, which is essential for effective recovery and neuroplasticity [7].

In the industrial sector, exoskeletons are utilized to enhance worker performance and reduce physical strain, thereby improving safety and productivity. These devices are designed to support workers in various tasks, such as lifting and carrying heavy loads, and can significantly reduce the risk of musculoskeletal injuries [33]. Companies like Kinova have developed robots for diverse applications, including medical assistance, rehabilitation, and mobile manipulation, demonstrating the versatility and adaptability of exoskeletons in different environments [34].

Additionally, lower limb exoskeletons are increasingly being used in military applications to enhance soldiers' endurance and mobility in challenging terrains. These devices provide soldiers with the necessary support and strength to carry heavy loads over long distances, thereby improving their operational effectiveness [1]. The adaptability of exoskeletons to various terrains, facilitated by advanced visual perception technologies, is crucial in military operations where soldiers often encounter unpredictable and rugged environments [5].

In recent years, the study of exoskeletons has expanded significantly, particularly in the realm of visual perception and environmental interaction. Understanding how these devices perceive their surroundings is essential for improving their functionality and user experience. Figure 3 illustrates the hierarchical structure of visual environment perception in exoskeletons, categorizing the role of visual sensors, challenges in terrain mapping, and advancements in visual perception technologies. This figure not only highlights the critical aspects of adaptability and technological integration but also emphasizes the ongoing challenges faced in enhancing exoskeleton functionality and user interaction. By examining these elements, we can better appreciate the complexities involved in developing more responsive and effective exoskeleton systems.

4 Visual Environment Perception in Exoskeletons

4.1 Role of Visual Sensors in Exoskeleton Adaptability

Visual sensors are pivotal in enhancing the adaptability of lower limb exoskeletons, enabling precise navigation in complex environments by interpreting surroundings to adjust to varying terrains and user needs, crucial for stability and safety [5]. As illustrated in Figure 4, this integration emphasizes three primary categories: the integration of high-level vision with low-level motion controllers, advanced actuator designs for real-time adjustments, and the application of advanced sensory technologies and AI-driven models for improved environmental perception and human-robot interaction. Systems integrating high-level vision with low-level motion controllers, such as Vision-Based Bipedal Locomotion Control (VBLC), exemplify the significant impact of visual sensors on adaptability [35]. Compliant actuator designs enhance these systems by allowing real-time force and position adjustments, reducing reliance on precise environmental models and improving robustness. Methods like the Variable Stiffness Actuator (VSA) effectively manage collision forces, enhancing user safety and comfort by significantly reducing peak forces [36, 37].

Advanced sensory technologies, including RGB, event-based data, LiDAR, and IMU readings, further augment environmental perception capabilities, improving adaptability by enabling exoskeletons to respond effectively to user movements and environmental changes [10]. Probabilistic models for action recognition and movement generation illustrate artificial intelligence's role in advancing exoskeleton technology, fostering intuitive human-robot interactions essential for wider adoption in assistive scenarios [8]. The development of modular sensor-based systems addresses challenges of traditional biomechanical assessments, offering more accessible evaluation and control of exoskeletons outside lab settings [9].

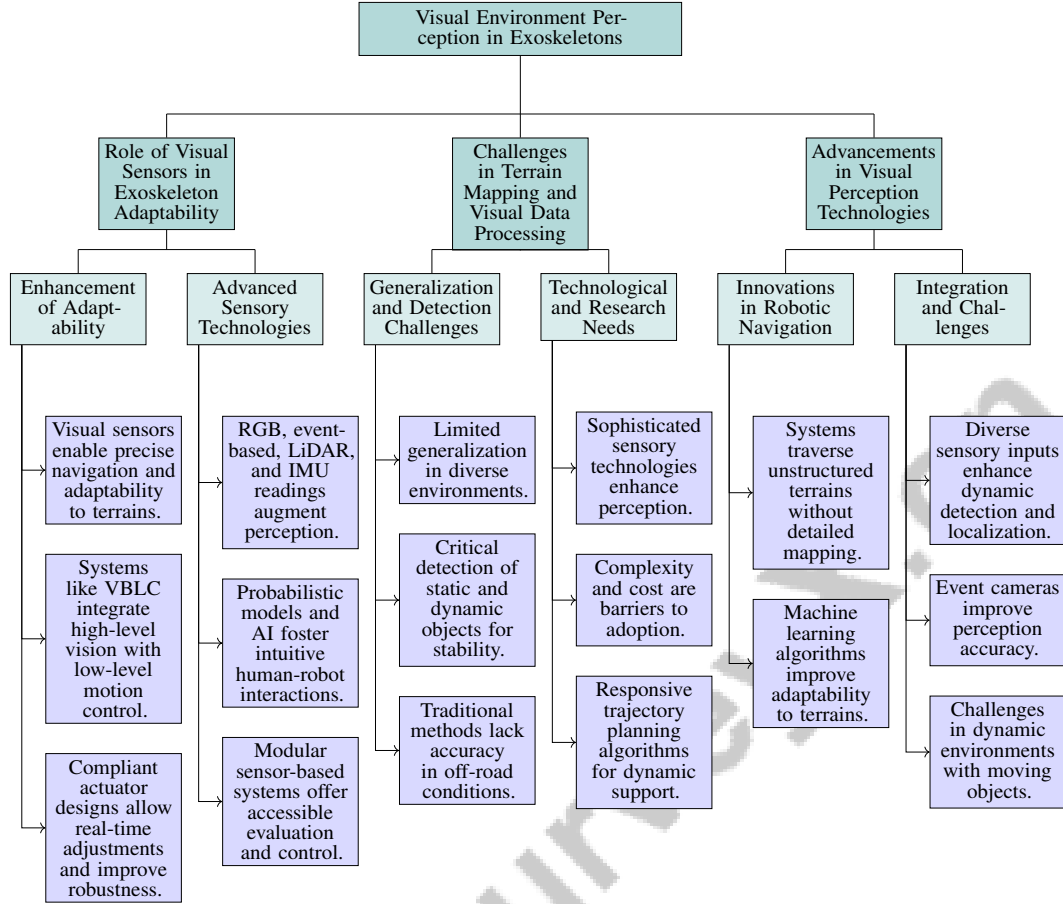


Figure 3: This figure illustrates the hierarchical structure of visual environment perception in exoskeletons, categorizing the role of visual sensors, challenges in terrain mapping, and advancements in visual perception technologies. It highlights the critical aspects of adaptability, technological integration, and ongoing challenges in enhancing exoskeleton functionality and user interaction.

4.2 Challenges in Terrain Mapping and Visual Data Processing

Overcoming challenges in terrain mapping and visual data processing is crucial for the advancement of lower limb exoskeletons, ensuring adaptability across diverse environments. A major issue is the limited generalization of current methods, which struggle with conditions differing from training scenarios, impacting real-world application where unpredictable terrains are common [38]. Accurate detection of static and dynamic objects is critical for user stability and safety, particularly in complex settings requiring effective human-machine collaboration to enhance performance through improved trust and adaptive interaction [25, 13, 39, 14, 40]. Traditional methods often lack accuracy in off-road conditions, where simulation struggles to replicate real-world dynamics.

Sophisticated sensory technologies, integrating RGB, event, LiDAR, and IMU data, represent significant advancements, enhancing environmental perception and enabling accurate terrain mapping [5]. However, the complexity and cost of these systems remain barriers to widespread adoption [9]. Responsive trajectory planning algorithms are essential for maintaining stability during dynamic locomotion, adapting in real-time to terrain changes to ensure continuous support and safety [41]. Despite advancements, further research is needed to enhance perception systems capable of managing real-world complexities and improving exoskeleton adaptability.

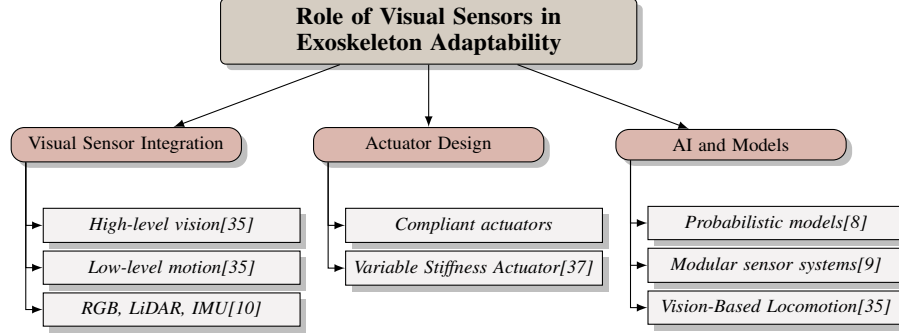


Figure 4: This figure illustrates the role of visual sensors in enhancing the adaptability of lower limb exoskeletons, emphasizing three primary categories: integration of high-level vision with low-level motion controllers, advanced actuator designs for real-time adjustments, and the application of advanced sensory technologies and AI-driven models for improved environmental perception and human-robot interaction.

4.3 Advancements in Visual Perception Technologies

Recent advancements in visual perception technologies have significantly improved the adaptability and functionality of lower limb exoskeletons, enabling efficient navigation in complex environments. Innovations in robotic navigation have led to systems that traverse unstructured terrains without detailed mapping, using learning offset behaviors and sensory integration to adapt to varying conditions and payloads, enhancing consistency and stability [42, 43, 20]. Machine learning algorithms, learning from raw visual inputs, reduce latency and improve adaptability to diverse terrains.

The integration of diverse sensory inputs, including RGB images, event-based data, LiDAR point clouds, and IMU readings, has been pivotal in enhancing visual perception for assistive robotics, facilitating accurate dynamic object detection and 3D localization [18, 44, 13, 14, 5]. Event cameras combined with other sensory data improve perception accuracy, crucial for user safety and stability in dynamic environments. Datasets combining RGB, event, point cloud, and IMU data support advanced algorithm development, enhancing assisted and independent living, particularly for the elderly in smart environments [5, 2, 45].

Despite these advancements, challenges in terrain mapping and visual data processing persist, especially in dynamic environments with moving objects complicating perception tasks [5]. Multi-sensory integration enhances exoskeleton perception robustness, yet real-world dynamics remain challenging [5]. Addressing these design and implementation challenges is critical for advancing assistive robotics, enabling exoskeletons to enhance mobility across various environments. Innovations like modular soft exoskeletons and virtually worn systems demonstrate potential for improving independence and quality of life, reducing energy expenditure, and mitigating traditional wearable robotics' discomfort and weight issues [27, 12]. Continued integration of cutting-edge visual perception technologies is essential for future effective assistive solutions.

5 Motion Pattern Recognition and Control Strategies

Category	Feature	Method
Learning-Based Approaches for Motion Pattern Recognition	Adaptive Interaction Systems	EMG-M[28]
Advanced Control Methods and Algorithms	Probabilistic Models	MEMM[10]
Integration of Sensory Feedback and Adaptive Control	Adaptive Feedback Integration	MSBS-GACC[9]
Applications in Various Fields	Exoskeleton Applications	uHRHI[7]

Table 1: This table provides a comprehensive summary of various methods and their applications in the field of lower limb exoskeletons. It categorizes the methods into learning-based approaches for motion pattern recognition, advanced control methods and algorithms, integration of sensory feedback and adaptive control, and applications in various fields. Each category highlights specific features and corresponding methods, showcasing the diversity and innovation in exoskeleton technology.

Understanding the operation of lower limb exoskeletons is critical for enhancing their design and functionality. Table 1 presents a detailed summary of the diverse methodologies and their applications in enhancing the functionality and adaptability of lower limb exoskeletons, as discussed in this section. Additionally, Table 2 provides a comprehensive comparison of different approaches and technologies used in the design and control of lower limb exoskeletons, as discussed in the section on motion pattern recognition and control strategies. This section explores methodologies for motion pattern recognition, emphasizing learning-based approaches that improve exoskeleton adaptability and effectiveness in rehabilitation and assistance. By examining foundational principles and key advancements, we can appreciate the innovations shaping assistive robotics.

5.1 Learning-Based Approaches for Motion Pattern Recognition

Learning-based approaches have significantly advanced lower limb exoskeletons by enhancing their adaptability and responsiveness to user movements. As illustrated in Figure 5, these approaches can be categorized into three key areas: neural network mechanisms, hierarchical models, and rehabilitation applications. Neural network-based adaptive feedback mechanisms utilize machine learning algorithms to process sensory data, improving user intention recognition [8]. The Maximum Entropy Markov Model (MEMM) captures the hierarchical structure of human activities, effectively recognizing diverse actions like Activities of Daily Living (ADLs) [10, 2]. Similarly, the State Conditioned Nonlinear Maps (SCN) method employs non-linear functions to dynamically adjust to varying task speeds and styles [10].

In rehabilitation, promoting voluntary control is crucial for neuroplasticity, especially in patients with neurological impairments [28]. Learning-based approaches facilitate this by adapting exoskeletons to users' natural movement patterns, enhancing rehabilitation outcomes [8]. Frameworks like Assistive Gym benchmark control algorithms and develop environments for diverse assistive tasks, pushing the boundaries of assistive robotics [31].

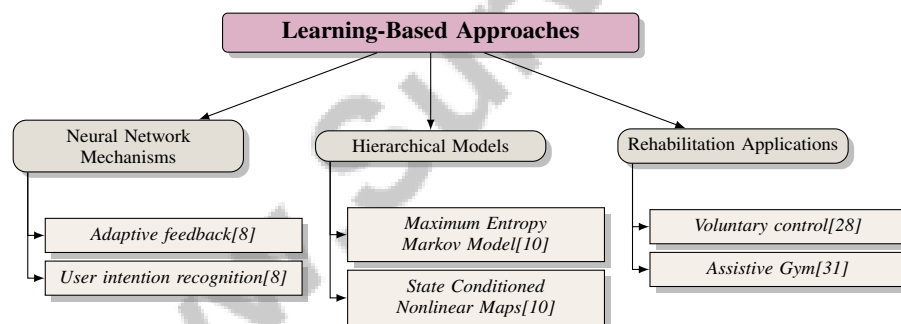


Figure 5: This figure illustrates key learning-based approaches for motion pattern recognition, categorizing them into neural network mechanisms, hierarchical models, and rehabilitation applications.

5.2 Advanced Control Methods and Algorithms

Advanced control methods are vital for effective lower limb exoskeleton function, enabling precise synchronization with users' natural movements. Physiological-based control strategies, using signals like electromyography (EMG) and electroencephalography (EEG), facilitate intuitive user-exoskeleton interactions, allowing real-time adaptation to user intentions [8]. The Hierarchical Lyapunov-based Cascade Adaptive (HLCA) control method enhances performance and safety by addressing control saturation and improving tracking, ensuring synchronization with users' natural gaits [6, 8].

Learning-based algorithms like MEMM recognize human activities in unstructured environments, enabling exoskeletons to adapt to task variations, crucial for personal assistive robotics [10]. Sensory feedback and adaptive control mechanisms further enhance exoskeleton functionality. Modular sensor-based systems using inertial measurement units, force-sensitive resistors, and load cells allow real-time biomechanical evaluation and control, ensuring user safety and comfort in dynamic environments [9, 5].

5.3 Integration of Sensory Feedback and Adaptive Control

Integrating sensory feedback and adaptive control mechanisms is essential for enhancing lower limb exoskeleton functionality and user experience. Sensory feedback systems provide real-time information on user movements and the environment, enabling exoskeletons to adjust operations accordingly [9]. This adaptability is crucial for ensuring user safety and comfort, particularly in unpredictable settings.

Advanced control methods, such as the Variable Stiffness Actuator (VSA) method, enhance adaptability by dynamically modifying stiffness and damping parameters based on terrain characteristics, improving user comfort and performance [45, 46, 23, 37, 47]. Learning-based approaches, including probabilistic models and MEMM, are critical for recognizing and adapting to diverse human motion patterns in real-time. This capability significantly enhances exoskeleton functionality, particularly for individuals with reduced motor performance, allowing precise monitoring of movement parameters through built-in sensors. Studies indicate that these advanced machine learning techniques improve action recognition accuracy, contributing to effective assistance in daily activities and enhancing quality of life in environments such as smart homes [2, 15].

5.4 Applications in Various Fields

Lower limb exoskeletons are applied across multiple fields, significantly enhancing mobility and performance. In healthcare, they assist individuals with mobility impairments, facilitating independence and improving quality of life. These devices are particularly valuable in rehabilitation, providing controlled assistance during repetitive task training, essential for effective recovery and neuroplasticity [7].

In industrial settings, exoskeletons enhance worker performance and reduce physical strain, improving safety and productivity. They support tasks like lifting and carrying heavy loads, significantly mitigating the risk of musculoskeletal injuries. Companies like Kinova illustrate the versatility of exoskeletons across applications, including medical assistance and mobile manipulation [34]. Additionally, lower limb exoskeletons are increasingly utilized in military applications to enhance soldiers' endurance and mobility in challenging terrains. These devices provide essential support for carrying heavy loads over long distances, improving operational effectiveness, particularly in unpredictable environments [1, 5].

Feature	Learning-Based Approaches for Motion Pattern Recognition	Advanced Control Methods and Algorithms	Integration of Sensory Feedback and Adaptive Control
Adaptability	User Movement Recognition	Real-time Adaptation	Real-time Feedback
Control Method	Neural Networks	Physiological Signals	Variable Stiffness Actuator
Application Field	Rehabilitation	Personal Robotics	Smart Homes

Table 2: This table offers a comparative analysis of various methodologies employed in the development of lower limb exoskeletons, focusing on their adaptability, control methods, and application fields. It highlights the role of learning-based approaches, advanced control methods, and the integration of sensory feedback in enhancing the functionality and utility of these devices across different domains.

6 Human-Machine Cooperation

Advancements in technology are transforming rehabilitation and mobility assistance, positioning human-machine cooperation as a crucial element in the design of lower limb exoskeletons. Soft exoskeletons, with their innovative mechanical designs and compliant structures, significantly enhance user comfort and adaptability, thereby improving mobility for individuals with impairments. Studies highlight these systems' ability to reduce energy expenditure during movement, underscoring the importance of control strategies that facilitate seamless interactions between users and exoskeletons to enhance independence and quality of life [16, 12]. This cooperation not only enhances device functionality but also improves user experience and satisfaction. Investigating cooperative control strategies is vital for understanding how these systems interpret user intentions and adapt responses, forming the foundation for effective human-machine collaboration.

6.1 Cooperative Control Strategies

Cooperative control strategies are pivotal for optimizing lower limb exoskeletons, enabling seamless user-device interaction. Intent-based control is central, allowing real-time adaptation of exoskeleton movements based on user actions [8]. Advanced control methods are essential for accurately interpreting user intentions, thereby fostering an intuitive user experience [7]. Physiological-based strategies, utilizing EMG and EEG, further enhance responsiveness, improving outcomes in rehabilitation and assistance [8].

As illustrated in Figure 14, the hierarchical structure of cooperative control strategies in assistive robotics is depicted, highlighting key categories such as intent-based control, advanced control methods, and physiological-based control. Each category contributes significantly to enhanced human-machine interaction and rehabilitation outcomes. The cooperative control strategies can be categorized into three main areas: intent-based control, trust and transparency, and modular sensor systems. Each category highlights significant aspects such as real-time adaptation, consistent performance, and personalized adjustments. Trust and transparency are paramount in human-machine interaction. High trust levels, fostered through consistent performance and advanced control strategies, ensure user confidence and comfort [30, 4]. Transparent control strategies providing clear feedback on exoskeleton actions are crucial for building trust and enhancing user experience [8]. Customization and user-centered design are critical for effective cooperation, tailoring exoskeletons to individual needs to ensure comfort, safety, and effectiveness [8]. Modular sensor-based systems facilitate personalized adjustments, promoting user adoption [9].

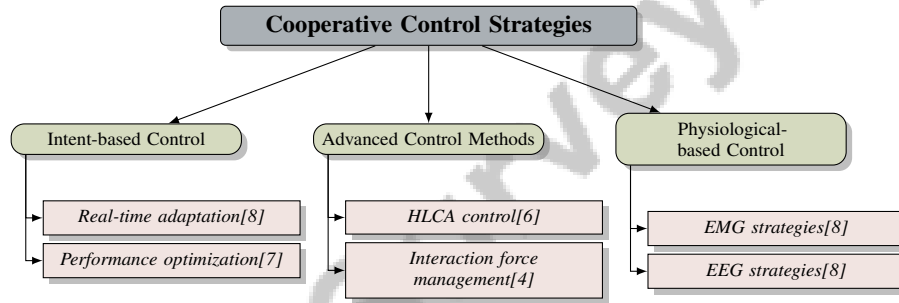


Figure 6: This figure illustrates the hierarchical structure of cooperative control strategies in assistive robotics, highlighting key categories such as intent-based control, advanced control methods, and physiological-based control, each contributing to enhanced human-machine interaction and rehabilitation outcomes.

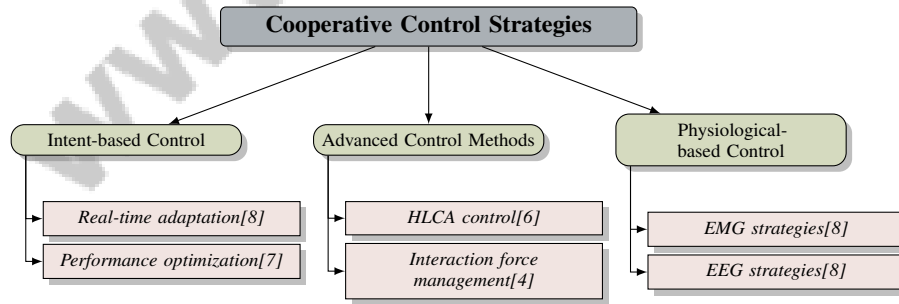


Figure 7: This figure illustrates the hierarchical structure of cooperative control strategies in assistive robotics, highlighting key categories such as intent-based control, advanced control methods, and physiological-based control, each contributing to enhanced human-machine interaction and rehabilitation outcomes.

6.2 Trust and Transparency in Human-Machine Interaction

Trust and transparency are essential in human-machine interaction with lower limb exoskeletons. Building trust is crucial for user compliance and maximizing rehabilitation potential [30]. Consistent

and reliable performance, supported by advanced control strategies ensuring safety and comfort, is fundamental to fostering trust [4]. Transparency, achieved through clear feedback on device actions, enhances user confidence and promotes exoskeleton adoption [8]. Intent-based control strategies improve trust by accurately aligning device movements with user intentions [8]. Additionally, physiological-based strategies enhance transparency by managing phase transitions and providing smoother assistance, thus improving comfort and device transparency, ultimately fostering greater trust [21, 23, 45, 15].

Haptic transparency significantly enhances interaction by providing accurate feedback on interaction forces and torques, ensuring safety and comfort while allowing users to maintain control [4]. User-centered design and customization further improve cooperation by tailoring exoskeletons to individual needs, ensuring a comfortable and effective experience [8]. Modular sensor-based systems offer accessible methods for evaluating and controlling exoskeletons outside laboratory environments, promoting widespread adoption [9].

6.3 User-Centered Design and Customization

User-centered design and customization are crucial in developing lower limb exoskeletons, ensuring devices meet diverse user needs and preferences. By focusing on specific user requirements, manufacturers can create effective, comfortable, and user-friendly exoskeletons, critical for promoting widespread adoption and accessibility for individuals with mobility impairments [8].

Customization involves developing adaptable control systems tailored to users' unique physical capabilities, ensuring optimal performance and satisfaction [8]. Modular sensor-based systems allow for real-time biomechanical evaluation and personalized assistance, enhancing user experience [9].

Innovative design approaches, incorporating advanced soft robotics and multicriteria optimization, improve usability and user acceptance while reducing energy requirements during movement, contributing to a better quality of life [12, 33]. Considerations such as weight, fit, adjustability, and user-friendly control interfaces facilitate intuitive interaction and enhance the overall effectiveness of exoskeletons.

As illustrated in Figure 15, the hierarchical structure of key concepts, innovations, and considerations in user-centered design and customization for lower limb exoskeletons is categorized into primary aspects, with references to relevant literature. This figure underscores the importance of developing user-centered design methodologies, which are pivotal in advancing assistive robotics, ensuring exoskeletons are functional, comfortable, and easy to use, thereby promoting widespread adoption and effectiveness [8].

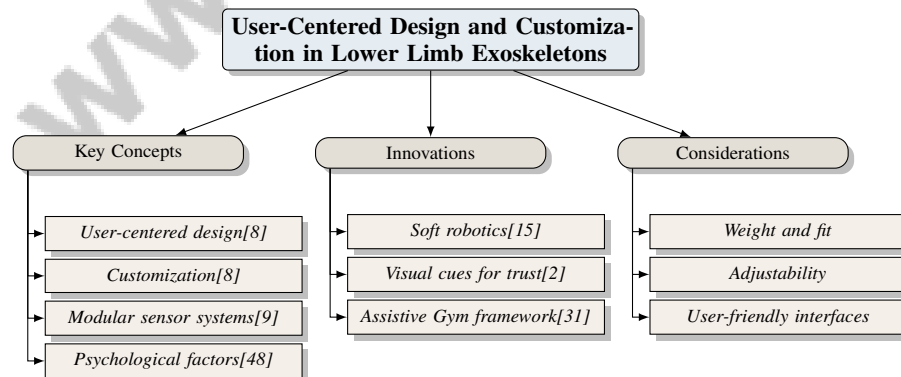


Figure 8: This figure illustrates the hierarchical structure of key concepts, innovations, and considerations in user-centered design and customization for lower limb exoskeletons. It categorizes the primary aspects into key concepts, innovations, and considerations, with references to relevant literature.

7 Terrain Adaptation and Challenges

7.1 Technological Approaches to Terrain Adaptation

The efficacy of lower limb exoskeletons as assistive devices hinges on their adaptability to varied terrains. Technological advancements have significantly improved this adaptability through sophisticated control strategies and actuation mechanisms, enabling safe and stable traversal of diverse surfaces such as flat ground, slopes, and granular terrains. For instance, the EXOSMOOTH project introduces a novel control strategy that manages phase transitions for smoother user assistance, while research on knee exoskeletons employs stiffness-based model predictive control to optimize performance on challenging surfaces like sand. These innovations enhance user comfort, reduce energy expenditure, and minimize muscle activation, promoting safer mobility assistance [45, 12, 8, 46, 23].

A pivotal approach involves integrating advanced sensory systems, including visual sensors and inertial measurement units (IMUs), to provide real-time data on user movements and environmental conditions. Enhanced visual perception technologies, such as RGB, event, and LiDAR sensors, have improved exoskeletons' ability to accurately perceive and interact with dynamic environments. This is exemplified by a multi-modal detection pipeline utilizing a comprehensive dataset for dynamic object detection and 3D localization, effectively addressing challenges in fusing 2D image and LiDAR data. Robust machine learning frameworks, particularly boosted learning approaches, enable exoskeletons to recognize a wide range of human actions with high accuracy, facilitating safer human-robot interactions and enhancing assistive technologies for individuals with mobility impairments, especially in smart living environments [5, 2]. These sensors allow exoskeletons to detect and identify static and dynamic objects, enabling real-time adaptation to terrain changes and improving user safety and stability.

As illustrated in Figure 17, the key technological approaches to enhancing terrain adaptability in lower limb exoskeletons focus on control strategies, sensory systems, and advanced control methods. This figure highlights the roles of soft robotics, advanced sensory systems, and reinforcement learning in improving adaptability, comfort, and efficiency. Each category showcases specific innovations and technologies that contribute to improved adaptability, user safety, and performance across varied terrains.

The implementation of reinforcement learning algorithms has shown promise in enhancing exoskeleton adaptability to diverse terrains [41]. These algorithms enable learning from environmental interactions, facilitating dynamic adaptation to terrain changes and optimizing performance [49]. Reinforcement learning techniques enhance the robustness and reliability of exoskeleton systems, particularly in off-road conditions where traditional simulation methods may fall short.

Moreover, advanced control methods, such as the Variable Stiffness Actuator (VSA) method, have further evolved exoskeleton technology, enhancing device adaptability and efficiency in navigating complex terrains. These advancements are crucial for ensuring effective user support across diverse environments, from healthcare to industry, and for providing reliable assistance in various applications [5].

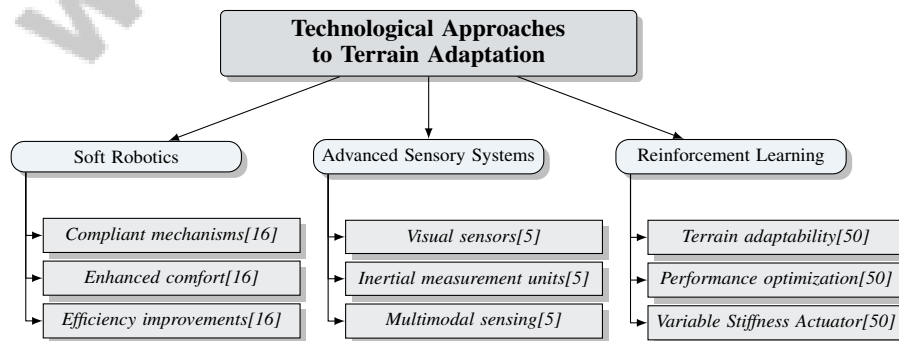


Figure 9: This figure illustrates the key technological approaches to enhancing terrain adaptability in lower limb exoskeletons, highlighting the roles of soft robotics, advanced sensory systems, and reinforcement learning in improving adaptability, comfort, and efficiency.

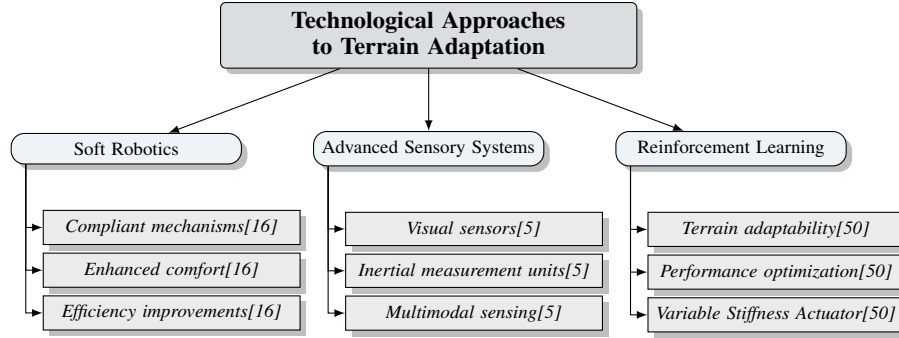


Figure 10: This figure illustrates the key technological approaches to enhancing terrain adaptability in lower limb exoskeletons, highlighting the roles of soft robotics, advanced sensory systems, and reinforcement learning in improving adaptability, comfort, and efficiency.

8 Human-Machine Cooperation

8.1 Cooperative Control Strategies

Cooperative control strategies are crucial for enhancing human-machine interaction in assistive robotics, particularly with lower limb exoskeletons. These strategies enable seamless collaboration by interpreting user intentions, thus improving rehabilitation and daily activities [8, 7]. Intent-based control is essential for real-time adaptation of exoskeleton movements, optimizing performance across assistive scenarios [8, 7]. Advanced methods, such as Hierarchical Lyapunov-based Cascade Adaptive (HLCA) control, enhance performance and safety by managing interaction forces and torques [6, 4]. Additionally, physiological-based control strategies, including electromyography (EMG) and electroencephalography (EEG), dynamically respond to user movements, enhancing rehabilitation effectiveness [8].

Figure 14 illustrates the hierarchical structure of cooperative control strategies in assistive robotics, highlighting key categories such as intent-based control, advanced control methods, and physiological-based control. Each of these categories contributes to enhanced human-machine interaction and rehabilitation outcomes, thereby emphasizing their significance in optimizing lower limb exoskeletons. As depicted in the figure, the focus on intent-based control, trust and transparency, and modular sensor systems underscores critical aspects such as real-time adaptation, consistent performance, and personalized adjustments, reinforcing the importance of these strategies in the context of assistive robotics.

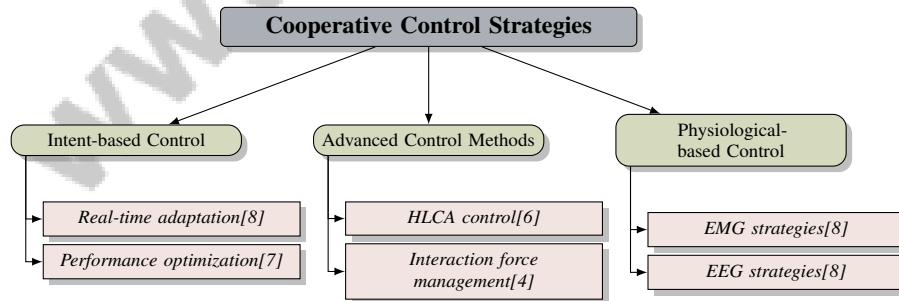


Figure 11: This figure illustrates the hierarchical structure of cooperative control strategies in assistive robotics, highlighting key categories such as intent-based control, advanced control methods, and physiological-based control, each contributing to enhanced human-machine interaction and rehabilitation outcomes.

8.2 Integration of Sensory Feedback and Adaptive Control

The integration of sensory feedback and adaptive control mechanisms significantly enhances the functionality of lower limb exoskeletons. Sensory feedback systems, utilizing technologies like iner-

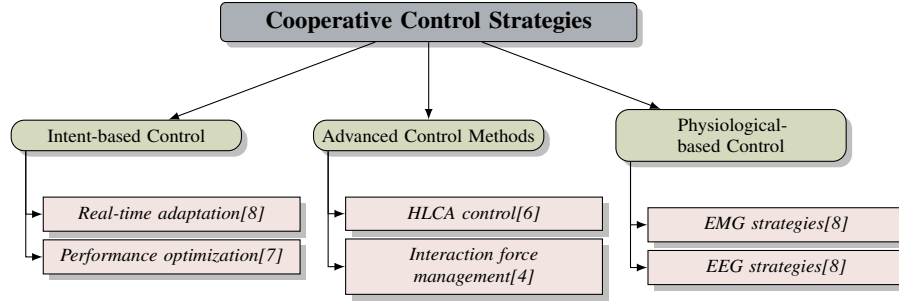


Figure 12: This figure illustrates the hierarchical structure of cooperative control strategies in assistive robotics, highlighting key categories such as intent-based control, advanced control methods, and physiological-based control, each contributing to enhanced human-machine interaction and rehabilitation outcomes.

tial measurement units and force-sensitive resistors, provide real-time data for dynamic adjustments, ensuring safety and comfort in unpredictable environments [9]. Adaptive control methods, such as the Variable Stiffness Actuator (VSA) approach, allow dynamic stiffness and damping adjustments, optimizing performance and comfort. The VSA principle, which enables compliant joints to absorb collision forces, has shown to significantly reduce peak forces transmitted to users [36, 16].

Unidirectional Human-Robot-Human Interaction methods further underscore the importance of sensory feedback by providing tailored haptic feedback for personalized rehabilitation [7]. Probabilistic models for human action recognition and movement generation represent a significant advancement in adaptive control, facilitating intuitive human-robot interactions [8].

Despite these advancements, challenges remain in optimizing exoskeleton design for effective, comfortable, and practical everyday use. Continued research into lightweight materials and advanced control systems is essential for improving functionality and effectiveness, aiming to enhance user comfort, energy efficiency, and simulate natural gait patterns [1, 22, 23, 12].

9 Human-Machine Cooperation

9.1 Cooperative Control Strategies

Cooperative control strategies are essential for optimizing human-machine interaction in lower limb exoskeletons by facilitating intuitive interfaces that accurately interpret user intentions. Intent-based control, leveraging physiological signals like EMG and EEG, ensures real-time adaptation to natural gait patterns, maximizing rehabilitation and assistive application efficiency [8]. Shared control systems enhance collaboration between user and exoskeleton, reducing user effort and maintaining balance, thus improving rehabilitation and user experience [30]. Advanced methods, such as Hierarchical Lyapunov-based Cascade Adaptive (HLCA) control, precisely manage interaction forces and torques, ensuring seamless cooperation and user safety [4]. Compliant control strategies, incorporating hysteretic damping, enhance model accuracy and stability, particularly in rehabilitation contexts.

As illustrated in Figure 14, which depicts the hierarchical structure of cooperative control strategies in assistive robotics, the key categories encompass intent-based control, advanced control methods, and physiological-based control. Each of these categories contributes significantly to enhanced human-machine interaction and rehabilitation outcomes, highlighting aspects such as real-time adaptation, consistent performance, and personalized adjustments. Integrating exteroceptive and proprioceptive data through advanced locomotion controllers enables dynamic data source switching, facilitating effective cooperative control [51]. Frameworks like Assistive Gym benchmark control algorithms and develop environments for diverse assistive tasks, advancing robotics adaptability to user needs [31].

9.2 Trust and Transparency in Human-Machine Interaction

Trust and transparency are vital for integrating lower limb exoskeletons in assistive applications, fostering user compliance and maximizing rehabilitation potential [30]. Trust is built through consistent

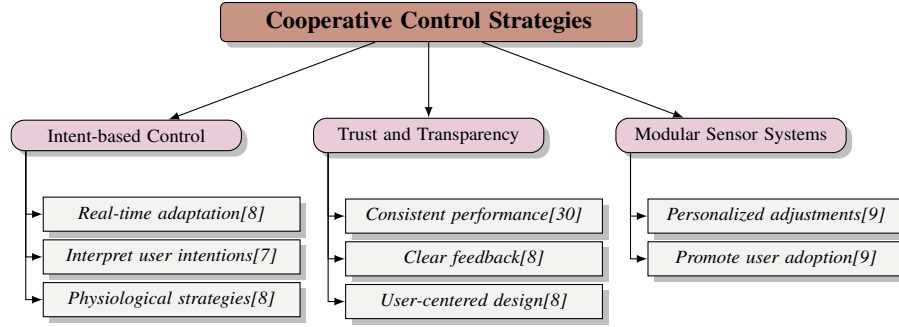


Figure 13: This figure illustrates the key cooperative control strategies for optimizing lower limb exoskeletons, focusing on intent-based control, trust and transparency, and modular sensor systems. Each category highlights significant aspects such as real-time adaptation, consistent performance, and personalized adjustments.

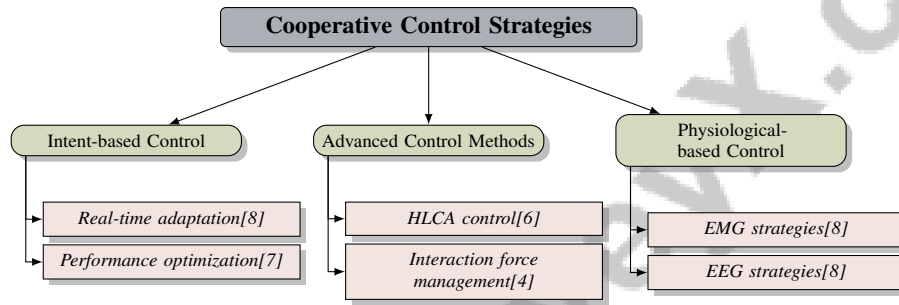


Figure 14: This figure illustrates the hierarchical structure of cooperative control strategies in assistive robotics, highlighting key categories such as intent-based control, advanced control methods, and physiological-based control, each contributing to enhanced human-machine interaction and rehabilitation outcomes.

performance and advanced control strategies prioritizing safety and comfort [4]. Transparent control strategies, providing clear feedback on exoskeleton actions, enhance user confidence by aligning device behavior with user intentions [8]. Intent-based systems support transparency by adapting operations in real-time, fostering trust in the technology. Engineering trust in human-machine interaction is challenging due to human behavior complexities and a lack of systematic development methods [25]. Addressing these challenges is crucial for effective exoskeletons across assistive scenarios. Schneider et al.'s quantitative estimation of human stubbornness advances personalized human-automation interactions [52]. Kapoor et al. emphasize user control and customization's impact on trust and comfort, highlighting the importance of user-centered design in enhancing exoskeleton effectiveness and experience [26]. Challenges remain in optimizing design and functionality for comfort and practicality, particularly regarding context-aware human intent inference methods dependent on sensor data quality [40].

9.3 User-Centered Design and Customization

User-centered design and customization are crucial for developing lower limb exoskeletons that meet diverse user needs, enhancing mobility, comfort, and user-friendliness, promoting wider technology adoption [8]. Customization involves adaptable control systems aligned with individual capabilities and preferences, ensuring optimal performance and satisfaction [8]. Modular sensor-based systems provide real-time biomechanical evaluation and personalized assistance tailored to user needs [9]. Addressing psychological factors influencing acceptance is essential, with future research focusing on user-friendly designs enhancing physical capabilities and psychological acceptance [48].

Integrating visual cues bridges communication gaps between humans and robots, enhancing experience and trust. As illustrated in Figure 15, the figure depicts the hierarchical structure of key concepts, innovations, and considerations in user-centered design and customization for lower limb

exoskeletons. It categorizes the primary aspects into key concepts, innovations, and considerations, with references to relevant literature, thereby providing a comprehensive overview of the field. Developing comfortable, user-friendly exoskeletons is crucial for adoption, particularly in aiding mobility for individuals with impairments. Innovations in soft robotics aim to improve usability and reduce energy requirements [15, 2, 45, 12]. Considerations such as weight, fit, adjustability, and user-friendly interfaces are vital for accessibility and benefit. Frameworks like Assistive Gym benchmark control algorithms and develop environments for assistive tasks, enhancing robotics adaptability to user needs [31]. Cooperative control and intent-based approaches enhance rehabilitation by enabling personalized, adaptive human-robot training [7].

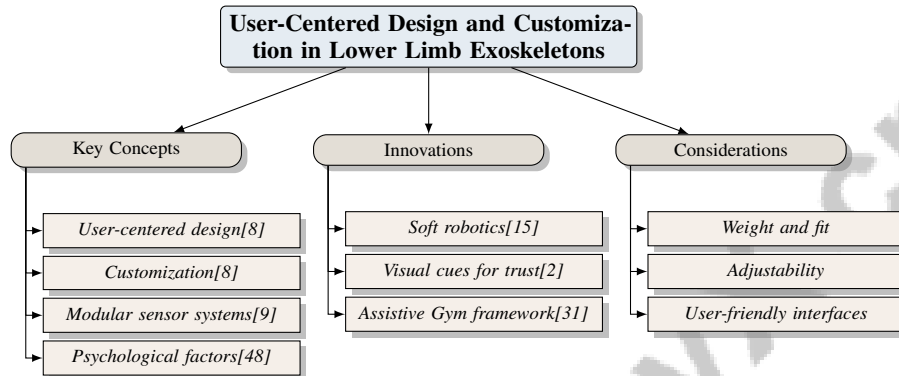


Figure 15: This figure illustrates the hierarchical structure of key concepts, innovations, and considerations in user-centered design and customization for lower limb exoskeletons. It categorizes the primary aspects into key concepts, innovations, and considerations, with references to relevant literature.

9.4 Terrain Adaptation and Challenges

Adaptability to diverse terrains is critical for lower limb exoskeletons' effectiveness. Technological advancements enable stable, safe navigation across surfaces. Sophisticated sensory systems, like visual sensors and IMUs, provide real-time data on movements and conditions, enhancing biomechanical evaluation, object detection, and robotic control, improving life quality for individuals with disabilities [5, 9, 2]. Advanced visual perception technologies, including RGB, event, and LiDAR sensors, improve exoskeletons' interaction with dynamic environments, vital for assistive robotics and supporting mobility-impaired individuals. Multimodal systems achieve robust 3D localization and action recognition, essential for safe, efficient navigation [5, 2, 5, 2]. Reinforcement learning algorithms enhance adaptability to diverse terrains by learning from environmental interactions, dynamically adapting to changes, and optimizing performance [41, 49]. Advanced control methods like the Variable Stiffness Actuator (VSA) method enhance adaptability and efficiency in navigating complex terrains, ensuring effective support in diverse environments, from healthcare to industry [5].

9.5 Reinforcement Learning and Real-World Adaptation

Reinforcement learning (RL) offers a promising approach for lower limb exoskeleton adaptability, enabling dynamic adjustments to optimize performance in changing terrains [49]. This adaptability ensures user safety and comfort in dynamic environments, where traditional control strategies may lack sufficiency [5]. RL improves robustness and reliability in off-road and unstructured environments by learning from real-world interactions, allowing exoskeletons to adapt to diverse needs and preferences, ensuring personalized, effective assistance [8, 49]. RL techniques enhance adaptability and efficiency in navigating complex terrains, paving the way for more effective assistive solutions. Advanced sensory technologies, like visual sensors and IMUs, enhance exoskeletons' perception and interaction with dynamic environments, providing real-time data for optimal performance and comfort [5, 9]. Despite these advancements, optimizing design and functionality for practicality and comfort remains challenging. Innovations in lightweight materials and control systems are expected to improve effectiveness, reduce energy expenditure, and facilitate integration with human gait patterns, enhancing independence and quality of life [1, 12].

9.6 Biomechanical and Environmental Considerations

Biomechanical and environmental considerations are critical for designing and implementing lower limb exoskeletons, directly impacting mobility and comfort [1]. Understanding biomechanics is essential for replicating natural human movement, necessitating precise engineering of mechanical components like actuators and sensors to provide support and flexibility for various activities [9]. Advanced sensory technologies, including visual sensors and IMUs, ensure exoskeletons effectively perceive and interact with their environment, providing real-time data on movements and conditions. RGB, event, and LiDAR sensors enhance navigation capabilities, improving user safety and stability. A multi-modal detection pipeline leverages these sensors for precise 3D localization and dynamic object detection, crucial for effective human-robot interaction, particularly for mobility-challenged individuals [45, 2, 5, 23, 15]. Compliant actuator designs, like the Variable Stiffness Actuator (VSA) method, enhance adaptability and efficiency in navigating complex terrains, ensuring effective support in diverse environments, from healthcare to industry [5]. Advanced control methods, such as the Hierarchical Lyapunov-based Cascade Adaptive (HLCA) control, improve performance and safety by enabling precise control over interaction forces and torques, ensuring seamless cooperation and enhancing user experience [6, 4].

10 Terrain Adaptation and Challenges

10.1 Technological Approaches to Terrain Adaptation

Adapting lower limb exoskeletons to varied terrains presents a significant challenge in assistive robotics, requiring innovative technologies to enhance functionality, safety, and usability in real-world scenarios. Advances in soft robotics, especially compliant mechanisms, offer promising solutions for improving adaptability, comfort, and efficiency for users with mobility impairments [16, 12, 8]. Key developments include integrating sophisticated sensory systems and control strategies, enabling exoskeletons to navigate dynamic environments with improved stability and safety.

As illustrated in Figure 17, this figure depicts the key technological approaches to enhancing terrain adaptability in lower limb exoskeletons, highlighting the roles of soft robotics, advanced sensory systems, and reinforcement learning in improving adaptability, comfort, and efficiency. Each category within the figure emphasizes specific innovations and technologies that contribute to improved adaptability, user safety, and performance across varied terrains.

Advanced sensory systems, such as visual sensors and inertial measurement units (IMUs), provide real-time data on user movements and environmental conditions, facilitating dynamic adaptation to changing terrains. Enhanced visual perception technologies, including RGB, event-based, and LiDAR sensors, are particularly beneficial for individuals with visual impairments, supporting safer human-robot interactions and robust algorithms for dynamic object detection and localization. Multimodal sensing systems enable exoskeletons to assess human motor performance better and optimize actions, augmenting functionality in diverse settings like smart homes [5, 2, 15, 27].

Reinforcement learning (RL) has also emerged as a promising method for enhancing terrain adaptability in exoskeletons. RL algorithms enable learning from environmental interactions, allowing for dynamic adaptation to various terrains and performance optimization [50]. Advanced control methods, such as the Variable Stiffness Actuator (VSA) method, further enhance adaptability and efficiency in navigating complex terrains, ensuring reliable user support across diverse applications [5]. Assistive Gym frameworks are instrumental in benchmarking control algorithms and developing environments for various assistive tasks [31].

10.2 Reinforcement Learning and Real-World Adaptation

Reinforcement learning (RL) is pivotal for enhancing the real-world adaptability of lower limb exoskeletons, especially in navigating complex terrains. RL algorithms facilitate dynamic learning from environmental interactions, enabling exoskeletons to adjust behavior, optimize performance, and ensure user safety [49]. This adaptability is crucial for functioning on uneven or soft surfaces, which challenge traditional control strategies [5].

RL-based control strategies allow exoskeletons to adapt to varied terrains and user needs, optimizing performance while ensuring safety and comfort [41]. Integrating RL with advanced sensory tech-

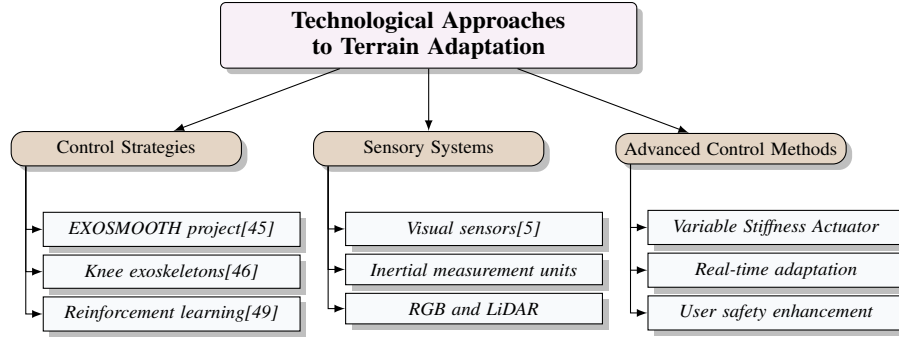


Figure 16: This figure illustrates the key technological approaches to terrain adaptation in lower limb exoskeletons, focusing on control strategies, sensory systems, and advanced control methods. Each category highlights specific innovations and technologies that contribute to improved adaptability, user safety, and performance across varied terrains.

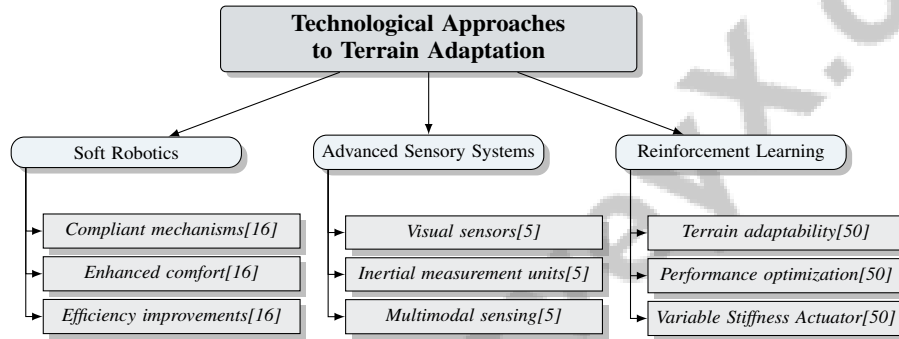


Figure 17: This figure illustrates the key technological approaches to enhancing terrain adaptability in lower limb exoskeletons, highlighting the roles of soft robotics, advanced sensory systems, and reinforcement learning in improving adaptability, comfort, and efficiency.

nologies, like visual sensors and IMUs, enhances exoskeletons' ability to perceive and interact with dynamic environments, providing real-time data for optimal operational adjustments [5]. Future research in RL and terrain adaptation aims to enhance datasets with dynamic obstacles, refine noise models, and integrate proprioceptive data for improved terrain reconstruction [53]. These advancements are essential for overcoming the limitations of traditional biomechanical assessment methods, often inadequate and costly for everyday use in lower-limb exoskeletons [9].

10.3 Biomechanical and Environmental Considerations

Adapting lower limb exoskeletons to various terrains requires understanding users' biomechanical constraints, such as diminished muscle force due to aging or disease, and environmental factors influencing gait dynamics, including terrain type and user movement patterns [48, 23]. Accurate perception and interpretation of environmental features, enabled by advanced sensory technologies like RGB, event, and LiDAR sensors, significantly enhance exoskeleton navigation in complex terrains. Machine learning algorithms allow exoskeletons to adapt movements based on environmental interactions, crucial for assistive scenarios ranging from rehabilitation to daily activities [50].

Advanced control methods, like the Variable Stiffness Actuator (VSA) method, enable dynamic adjustments of stiffness and damping parameters in response to changing conditions, ensuring optimal performance and user comfort. VSA utilizes compliant joints to absorb collision forces, reducing peak forces transmitted to the user during interactions with external objects, enhancing safety and comfort, particularly in powered lower-limb exoskeletons [36, 32]. Environmental considerations are critical for effective exoskeleton operation, as these devices must navigate diverse terrains with precision and safety. RL applications show promise in enhancing real-world adaptation and performance, enabling exoskeletons to learn from environmental interactions and ensure user safety and comfort in dynamic environments where traditional control strategies may be inadequate [5].

11 Future Directions in Assistive Robotics

11.1 Advanced Machine Learning and Adaptability

Integrating advanced machine learning techniques into lower limb exoskeletons marks a significant leap forward, enhancing adaptability and functionality in dynamic settings. This is illustrated in Figure 18, which depicts the integration of neural networks, reinforcement learning, and cooperative control to improve adaptability, performance, and personalized rehabilitation in these devices. Neural networks enable exoskeletons to learn from user interactions, optimizing performance tailored to individual needs under diverse conditions [8]. Progress in assistive robotics hinges on exploring complex neural network architectures and balanced datasets across tasks. Reinforcement learning (RL) emerges as a pivotal strategy, allowing exoskeletons to adjust operations dynamically based on environmental interactions, crucial for optimizing performance and ensuring safety in unstructured terrains [49, 50]. The robustness and reliability of exoskeleton systems are notably improved through RL applications, particularly in challenging conditions. Frameworks like Assistive Gym provide essential benchmarks for evaluating control algorithms and developing environments for assistive tasks, advancing the field significantly [31]. Cooperative control and intent-based approaches further enhance rehabilitation by facilitating personalized human-robot training programs [7]. Despite advancements, optimizing exoskeleton design for effective, comfortable, and practical use remains challenging. Future research should focus on enhancing model robustness to speed variations, optimizing trajectories for obstacle avoidance, and exploring applications beyond human-robot interaction. Incorporating ligaments into musculoskeletal models and investigating alternative evaluation methods for joint configurations can improve measurement accuracy [32].

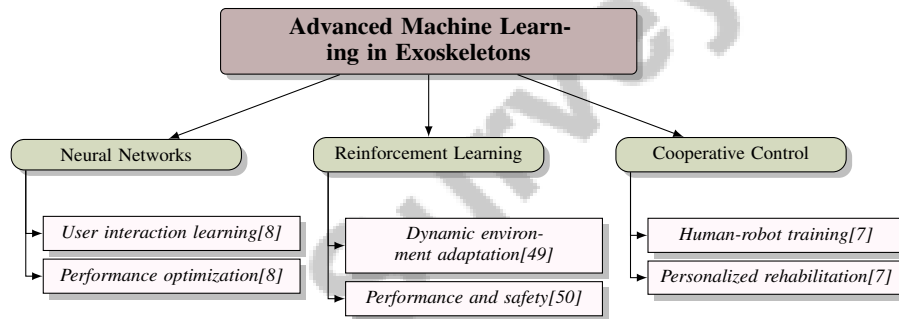


Figure 18: This figure illustrates the integration of advanced machine learning techniques in lower limb exoskeletons, focusing on neural networks, reinforcement learning, and cooperative control to enhance adaptability, performance, and personalized rehabilitation.

11.2 User-Centric Design and Feedback Mechanisms

Advancements in user-centric design and feedback mechanisms are crucial for enhancing user experience and promoting the adoption of lower limb exoskeletons. Tailoring these devices to meet diverse individual needs enhances mobility, assistance, comfort, and usability [8]. Emphasizing user-centric design methodologies through physical robot experiments and exploring anthropomorphism in robot design is vital for understanding psychological factors influencing user acceptance [26]. Developing diverse control and feedback mechanisms is necessary to ensure exoskeletons effectively support users in unpredictable environments. Advanced sensory technologies, such as visual sensors and inertial measurement units (IMUs), provide real-time feedback on user movements and environmental conditions, enabling dynamic adjustment of assistance levels and optimizing efficiency [12, 16, 45, 15]. The integration of RGB, event, and LiDAR sensors significantly enhances navigation capabilities in complex terrains, improving user safety and stability. Intent-based control strategies and cooperative approaches enhance rehabilitation by facilitating personalized human-robot interactions, ensuring reliable assistance across diverse environments [7].

11.3 Applications and Real-World Testing

Lower limb exoskeletons hold significant potential across sectors such as healthcare, industry, and military, each presenting unique challenges and opportunities. In healthcare, they support

Benchmark	Size	Domain	Task Format	Metric
TRB[54]	1,000	Legged Robotics	Terrain Evaluation	Heuristic Foothold Score
EXOSMOOTH[45]	15	Robotics	Assisted Walking	Smoothness, Transparency
Gibson[55]	211,000	Robotics	Local Planning	Real-World Transfer Error, Navigation Complexity
EXPERIENCE[56]	5	Wearable Robotics	Physiological Assessment	GSR, HR
AG[57]	1,000,000	Assistive Robotics	Reinforcement Learning	Mean Reward
BM-ADL[2]	7,767	Human-Computer Interaction	Activity Recognition	Accuracy, Class Precision

Table 3: This table presents a comprehensive overview of various benchmarks used in the evaluation of robotic systems, specifically focusing on their application domains, task formats, and performance metrics. The benchmarks span a range of robotic applications, including legged robotics, wearable robotics, and assistive robotics, highlighting the diversity in tasks from terrain evaluation to activity recognition.

rehabilitation by assisting individuals with mobility impairments, facilitating consistent assistance during repetitive task training, which is vital for recovery and promoting neuroplasticity [7]. In industrial settings, exoskeletons enhance worker performance and safety by reducing physical strain during tasks like lifting, lowering musculoskeletal injury risks [33]. Advanced technologies, including visual perception and motion pattern recognition systems, augment adaptability to various work environments, enabling precise navigation in dynamic settings [5]. In military applications, exoskeletons enhance endurance and mobility, supporting soldiers in carrying heavy loads over challenging terrains, critical for operational effectiveness [1]. Frameworks like Assistive Gym are instrumental in comparing control algorithms and developing environments for diverse tasks, ensuring exoskeletons meet varied user needs [31]. Cooperative control and intent-based approaches further enhance rehabilitation processes by fostering personalized training programs [7]. Despite technological advancements, challenges in optimizing design and functionality for everyday use persist. Researchers must focus on enhancing effectiveness, comfort, and practicality through compliant mechanisms that improve adaptability and safety. Current studies emphasize innovative actuator placements and control strategies to support users with mobility impairments, ensuring seamless daily integration while addressing user acceptance and energy efficiency issues [15, 22, 16, 12]. Ongoing research in lightweight materials and innovative control systems holds potential for further enhancing exoskeleton performance in rehabilitation and assistance. Real-world testing, supported by benchmarks and frameworks, as demonstrated by Zhang et al., is crucial for evaluating exoskeleton performance across diverse terrains, laying a foundation for future development [54]. Table 3 provides a detailed comparison of benchmarks used in the real-world testing of robotic systems, illustrating their relevance across different application domains and tasks. Advanced sensory technologies, including visual sensors and IMUs, are essential for providing real-time feedback, enhancing action and movement recognition accuracy, and supporting robust human-robot interactions. Combining RGB and LiDAR data in assistive robotics shows promise in improving 3D localization, underscoring the need for refining multi-modal detection systems to assist users, particularly those with visual impairments [5, 2]. These technologies enable precise navigation of complex terrains, enhancing user experience and promoting the widespread adoption of exoskeleton technology.

12 Conclusion

Lower limb exoskeletons stand as a pivotal advancement in assistive robotics, significantly enhancing human mobility and adaptability across various domains. These devices have proven instrumental in rehabilitation and movement assistance, markedly improving the quality of life for individuals with mobility impairments. The integration of advanced technologies, such as visual environment perception and motion pattern recognition, has been fundamental in elevating the functionality of exoskeletons within complex environments.

The deployment of visual sensors, including RGB cameras, event cameras, LiDAR, and inertial measurement units (IMUs), has substantially augmented the environmental perception capabilities of exoskeletons, facilitating precise terrain mapping and navigation. These technologies enable exoskeletons to interact effectively with both static and dynamic objects, thereby enhancing user safety and stability. Moreover, the development of learning-based algorithms for motion pattern

recognition has increased the adaptability and efficiency of exoskeletons, allowing for real-time recognition and response to human motion patterns.

Effective human-machine cooperation is essential, with cooperative control strategies and intent-based approaches fostering seamless interaction between users and exoskeletons. These strategies ensure accurate interpretation of user commands and real-time adaptation of operations, optimizing performance and enhancing the user experience.

Frameworks like Assistive Gym provide benchmarks for comparing control algorithms and developing environments for diverse assistive tasks, advancing the field of assistive robotics. Such frameworks are crucial for evaluating and refining control strategies, ensuring exoskeletons are effective and adaptable to diverse user needs. Additionally, the integration of advanced machine learning techniques, including reinforcement learning, holds significant promise for enhancing the adaptability and efficiency of exoskeletons in navigating complex terrains.

Despite these advancements, challenges remain in optimizing exoskeleton design and functionality to ensure effectiveness, comfort, and practicality for everyday use. Continued research in lightweight materials, innovative control systems, and advanced sensory technologies is vital for further enhancing the performance of lower limb exoskeletons in rehabilitation and assistance applications. Future research should also address the limitations of traditional biomechanical assessment methods, which are often inadequate and costly for everyday use in lower-limb exoskeletons.

The potential societal impact of lower limb exoskeletons is substantial, enhancing human mobility and adaptability across various sectors, including healthcare, industry, and military applications. These devices have already demonstrated significant benefits in rehabilitation and movement assistance, improving the quality of life for individuals with mobility impairments. As research progresses, further advancements are anticipated, leading to more innovative and effective solutions for individuals with mobility challenges.

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