International Journal of Scientific Research in Engineering and Management (IJSREM)
Volume: 09 Issue: 04 | April - 2025 SJIF Rating: 8.586 ISSN: 2582-3930

Design and Simulation of Exoskeleton Mechanism to Assist Paralyzed Patients: A Review

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Abstract - Exoskeletons have emerged as a promising assistive technology for paralyzed patients, offering mobility restoration and rehabilitation benefits. This review paper explores the design and simulation aspects of exoskeleton mechanisms, focusing on their structural configurations, actuation methods, control strategies, and simulation techniques. The study highlights recent advancements in exoskeleton technology, challenges in implementation, and future research directions to enhance their efficiency and accessibility for paralyzed individuals.

Key Words**:** Exoskeleton, Paralysis, Rehabilitation Robotics, Actuation, Control Systems, Simulation

1.INTRODUCTION

Paralysis, caused by spinal cord injuries (SCI), strokes, or neurological disorders, severely limits mobility and independence. Traditional wheelchairs provide limited assistance, whereas exoskeletons offer dynamic support by augmenting limb movements. Recent advancements in robotics, materials science, and control systems have improved exoskeleton designs, making them viable for medical applications. The development of exoskeleton system has revolutionized the field of rehabilitation, offering new hope for peoples with paralysis. These wearable robotic devices designed to assist and enhance human movement, enabling paralyzed patient to stand, walk and provide mobility and independence. My project is mainly dedicated to all the paralyzed patient who can't move their lower part body. This type of patient usually uses wheelchair or someone else assistance to move or any kind of mobility-based work. This project introducing so they can sit, stand and walk. This will support their body and maintain balance. The revolution of robotic exoskeleton started at the last half of the 20th century. People who were unable to move or walk began to adopt robots. In 1965, General Electric (in the US) was in progress with the Hardiman, a large full-body exoskeleton intended to enhance the user's strength to assist in lifting heavy objects. At the end of 1960s and at the start of 1970s, the first gait assistance exoskeletons were developed at the Mihajlo Pupin Institute Serbia and University of Wisconsin-Madison in the US, respectively. During the past decade, enormous progress has been made in the development of exoskeletons. Exoskeleton are wearable robotic systems, which can provide the balanced and mobility by applying external force/torque to their lower limbs with the equipped actuators. Exoskeleton are humane machine cooperative systems and integrate both human intelligence and robot power. In recent time Exoskeleton modified and commercialized by many companies such as ReWalk, Ekso GT, and Phoenix Medical. They had more advance technology their exoskeleton is better and faster control system. They primarily made for rehabilitation for paralyzed people but also can be used for their day-to-day application. With advanced technology they become highly expansive come at price far beyond reach for middle class and poor people. Despite significant advancement, high cost of exoskeleton remains a major problem. This project aims to address this challenge by focusing on the design of cost-effective exoskeleton system. By leveraging innovative mechanism, simple control system, materials, and manufacturing processes, this study seeks to design affordable exoskeleton without compromising on performance.

This paper reviews:

- Mechanical design considerations for exoskeletons.
- Actuation and control mechanisms.

- Simulation techniques for performance validation.
- Challenges and future trends.

2. UNDERSTANDING BIOMECHANICAL MODELING IN EXOSKELETON DEVELOPMENT

Biomechanical modeling plays a crucial role in the design and development of lower-limb exoskeletons. Here are some key aspects of how these models are utilized:

2.1 Biomechanical Modeling

The realm of biomechanical models commonly involves two main categories: conceptual models and detailed models. These models play a crucial role in understanding human movement patterns and motor control in the development of lower-limb assistive devices.

- Conceptual models: Provide an abstract representation of human movement patterns using basic mechanical elements and simplistic control circuitry.
- Detailed models: Include complex mathematical formulations to address various biomechanical aspects such as musculoskeletal structure, muscle-level actuation, and neural control.

2.2 Exoskeleton Design

Biomechanical models help identify optimal joints for assistance, which is essential for effective exoskeleton design. They inform structural arrangements and optimize mechanical properties and geometries, allowing for pre-prototyping evaluations through predictive capabilities

- Exoskeletons are designed with multiple degrees of freedom (DOFs) to replicate natural joint movements, as seen in ankle rehabilitation devices (Sergazin et al., 2024) (Sergazin et al., 2024).
- Simulation tools like Adams are utilized to analyze movement and optimize joint configurations (Guo, 2024).
- The integration of robotic methodologies and gait analysis enhances the design process, ensuring that exoskeletons align with human biomechanics (Medrano-Hermosillo et al., 2024).

3. CONTROL SYSTEM IN THE EXOSKELETON ROBOT

The control system proposed in this research for the lower limb rehabilitation exoskeleton robot is designed to facilitate effective rehabilitation for patients with lower limb motor dysfunction. Here are the key components and functionalities of the control system:

- Closed-Loop Control: The control system implements closed-loop position control and trajectory planning for each joint mechanism of the exoskeleton. This allows for precise adjustments based on real-time feedback from the robot's sensors, ensuring that movements are accurate and responsive to the user's needs.
- Hardware Components: The control system consists of various hardware elements, including sensors, motor drivers, servo motors, and encoders. These components work together to execute the desired movements of the exoskeleton, enabling it to assist patients in performing daily activities such as walking, standing up, and climbing stairs.
- Human-Machine Interaction: The system is designed for real-time interaction with the user. It can quickly adapt to different motion patterns, which is crucial for rehabilitation training. The human-machine interaction signals and algorithms are optimized for fast response times, allowing the exoskeleton to adjust its movements in sync with the user's actions.
- Trajectory Planning: An innovative human-machine gait joint moment cycle learning algorithm is utilized to compute the degree of human-machine rejection. This helps in refining the ideal trajectory for the exoskeleton's movements. A fuzzy controller is also integrated to enhance trajectory reprogramming and tracking capabilities, ensuring that the exoskeleton can follow the user's intended movements accurately.
- User Control Modes: Patients can operate the exoskeleton in various modes, such as standing up, sitting down, and continuous walking, using controls mounted on the crutch segment. This user-friendly interface allows patients to engage actively with the rehabilitation process.
- Performance Validation: The control system's effectiveness was validated through a series of performance experiments, including robot angle response tests and trajectory tracking experiments. These tests demonstrated the exoskeleton's ability to quickly adjust to different angles and accurately track movements, with a maximum tracking error of ±5°

- Model Predictive Control (MPC):

The core of the control system is the MPC architecture, which allows for advanced prediction of human torque based on electromyography (EMG) signals. This prediction enables the system to select appropriate assistance modes dynamically during operation.

- Fuzzy Logic Algorithm (FLA):

The FLA plays a crucial role in determining the assistance mode based on human involvement. It adjusts the robot's compliance, allowing for varying levels of human contribution to the rehabilitation task. The assistance modes include:

Passive Mode: The robot dominates, allowing the human to relax.

Active-Assist Mode: The human cooperates with the robot in the task.

Safety Mode: Engaged when human resistance to the robot is detected.

- Real-Time Operation: The control system operates in real-time, with the controller and actuator code running at 500 Hz. The EMG signals are processed at a higher frequency of 2048 Hz, ensuring timely responses to human movements and conditions.

- Human-Robot Interaction: The system is designed to adapt to different human involvement conditions, demonstrating its capability to track a sinusoidal reference trajectory while adjusting to the user's needs. This adaptability is crucial for effective rehabilitation

4. SIMULATION IN THE LOWER LIMB EXOSKELETON STUDY

The paper presents a comprehensive simulation of a lower limb exoskeleton walking assist mechanism, focusing on both kinematics and dynamics to ensure effective rehabilitation for patients with limited mobility. Here are the main aspects of the simulation discussed in the paper.

- Software Utilization: The simulation was conducted using ADAMS software, which is designed for multi-body dynamics analysis. This software is essential for modeling and simulating the mechanical behavior of the exoskeleton, allowing for detailed analysis of its performance during movement

- Model Development: The simulation process began with the creation of a 3D model in SolidWorks, which was then converted and imported into ADAMS. This step included adding material properties to the components, specifically using aluminum alloy for the exoskeleton structure, and setting gravity in the positive Y direction to simulate real-world conditions

- Setting Constraints and Parameters: The simulation involved defining various constraints and driving parameters. Contact constraints were established between the footplate and the ground to simulate friction during walking. Additionally, rotation driving forces were applied at the knee and hip joints to facilitate the movement of the exoskeleton.

- Results and Analysis: After running the simulation, the results provided insights into the torque of each active joint and the human-machine contact force. The analysis of the angle and angular velocity curves of each joint indicated that the movements were smooth and stable. The overall gait was synchronized, with the left and right feet completing steps in a coordinated manner

- Performance Verification: The kinematics and dynamics performance of the walking assist mechanism was verified through the simulation results. The findings confirmed that the exoskeleton met the necessary requirements for movement space, performance, and dynamics, making it suitable for assisting patients with lower limb movement limitations

5. ACTUATORS

Decades ago, rigid robotic structures were prevalent in the industry, but there has been a shift towards more adaptive and compliant robots inspired by human body mechanisms. The Series Elastic Actuator (SEA) pioneered compliance in robots, using a spring to absorb shocks and enhance dynamic performance.

- The SEA employed a spring as a low pass filter to enhance dynamic performance.

- However, the SEA lacked adaptability in compliance levels, leading to the development of Variable Stiffness Actuators (VSAs) by researchers.

Variable Stiffness Actuators (VSAs):

- VSAs can independently change the stiffness of the output link, unlike SEAs.

- Adjusting stiffness in VSAs enhances safety, speed, efficiency, adaptability, and force accuracy during human-robot interactions, providing benefits in various applications like assistive devices, rehabilitation, exoskeletons, and haptics.

Implementation of VSAs:

- VSAs can be configured in series or antagonistic setups, with the latter resembling mammalian anatomy for joint actuation.

- Energy efficient VSA designs like the lever arm mechanism have been developed, reducing energy requirements for stiffness regulation without changing the pretension of the elastic element.

Concept of Lever Mechanism in Stiffness Regulation

The section introduces the concept of changing stiffness utilizing a lever mechanism with essential elements:

- A lever is depicted as a bar rotating around a pivot point, with springs attached on both sides to add compliance.

- Essential components of a lever include the pivot point, springs, and the force application point.

- By adjusting the lever's effective arm (distance between pivot and springs), stiffness at the lever end can be modified.

- The stiffness of the lever depends on the maximum effective arm length and the spring stiffness.

- Two variations of the lever mechanism are discussed:

- Variable lever arm method where stiffness is adjusted by changing the effective arm length.

- Variable ratio lever mechanism where stiffness is fine-tuned by altering the pivot position relative to the springs and force application point.

- In the "Energy efficient variable stiffness actuator," stiffness is altered by changing the force application point while keeping springs fixed.

- The lever's stiffness can be calibrated by modifying the effective arm length; a shorter arm yields higher stiffness.

- This mechanism is suitable for linear actuators but not for rotary versions.

Stiffness Characteristics

The section explains the mechanical realization of each actuator in the AwAS family, highlighting differences in stiffness characteristics between AwAS-II, CompACT VSA, and AwAS actuators.

Mechanical Realization

The stiffness regulation in the AwAS mechanism is influenced by parameters like spring stiffness (k_s) and arm length (r):

- Stiffer springs achieve higher maximum stiffness with a shorter arm length, but require a stronger structure and a more powerful motor due to increased internal stress from pre-compression.

- Softer springs reduce the lower stiffness limit, enabling the use of a lighter structure and smaller motor, but demand a longer arm length to reach maximum stiffness.

6. CHALLENGES AND FUTURE TRENDS

6.1 Current Challenges

- Power Consumption: Battery life limitations restrict prolonged use.

- Cost: High manufacturing expenses hinder widespread adoption.

- User Adaptation: Requires extensive training for optimal use.

6.2 Future Directions

- AI-Enhanced Control: Machine learning for adaptive gait assistance.

- Soft Exoskeletons: Flexible, lightweight designs for comfort.

- Hybrid Actuation: Combining multiple actuation methods for efficiency.

7. Literature Review

[1] Mostafijur Rahman, et al. “Kinematics Mathematical Modelling of Lower Limb Exoskeleton for Paralyzed Stroke Patients.” Kinematics mathematical modelling of lower limb exoskeleton for paralyzed stroke patients aims to develop a rehabilitation robot for bedridden patients. The robot will provide motion assistance throughout the human’s wide range of motion and is designed based on kinematic analysis and mathematical modelling.

[2] Khin Yadana Kyaw, et al. “Kinematic and Dynamic Equations for the Design and Simulation of 2DOF PID-Controlled Exoskeleton.” This study addresses the design and simulation of a 2-DOF PID-controlled exoskeleton for hemiplegic patients, aiming to enhance rehabilitation outcomes. Gait analysis and motion capture studies were used to learn more about the walking patterns of the

patients. The modular design of the exoskeleton, which is tailored to human physiological traits, attempts to avoid joint damage. Denavit-Hartenberg parameters were used to generate kinematic and dynamic equations, which allowed for precise exoskeleton control. The correctness of the model was confirmed using MATLAB simulations, which also showed that it was flexible enough to accommodate different mass distributions. The performance and dependability of the exoskeleton were demonstrated by the experimental findings, with PID (Proportional-integral-derivative) control guaranteeing accurate movement. For individualised rehabilitation, future studies could investigate sophisticated control techniques and machine learning integration.

[3] Yuanxi Sun, et al. "Design and Motion Control of Exoskeleton Robot for Paralyzed Lower Limb Rehabilitation." This paper provides a comprehensive examination of the advancements in lower limb exoskeleton technology. It highlights the evolution from basic sensing mechanisms to sophisticated control systems that enhance mobility for individuals with disabilities. The review categorizes various sensing technologies, such as force sensors and motion capture systems, and discusses their integration into exoskeletons to improve user experience and functionality. Furthermore, it emphasizes the importance of control strategies, including adaptive and predictive algorithms, which allow exoskeletons to respond effectively to user movements and environmental changes. The systematic review also identifies gaps in current research, suggesting areas for future exploration to optimize the design and application of lower limb exoskeletons for rehabilitation and assistance in daily activities.

[4] Christopher Caulcrick, et al. "Model Predictive Control for Human-Centred Lower Limb Robotic Assistance." The paper discusses a model predictive control (MPC) framework designed for lower limb exoskeletons, focusing on enhancing human-robot interaction during rehabilitation. It addresses the challenges of assist-as-needed (AAN) control, which is crucial for accommodating the diverse needs of patients with mobility impairments due to neural trauma. The proposed system utilizes a fuzzy logic algorithm (FLA) to determine three distinct modes of assistance: passive mode, where the robot takes over; active-assist mode, where the human collaborates with the robot; and safety mode, which activates when the human resists the robot's movements. By estimating human torque from electromyography (EMG) signals, the MPC can predict necessary torque adjustments and switch between assistance modes effectively. Experimental results with a 1-degree-of-freedom knee exoskeleton demonstrated the system's ability to transition smoothly among these modes, showcasing its potential for improving mobility assistance and rehabilitation outcomes through enhanced human-robot synergy

[5] Yixuan Zhao et al. "Kinematics and Dynamics Simulation of Lower Limb Exoskeleton Walking Assist Mechanism." The paper presents a lower limb exoskeleton walking assist mechanism designed for patients with limited mobility. It includes kinematics and dynamics simulation using ADAMS software, confirming the mechanism's effectiveness in meeting movement and dynamic performance requirements for rehabilitation.

[6] E. A. A. Salcido et al. "Design of an Exoskeleton for the Lower Limbs: Sturdy Control, Simulation, and Experimental Findings The creation of a reliable control algorithm for use in an exoskeleton for the knee and ankle joints intended to aid in the rehabilitation of flexion and extension movements is presented in this study. Following the path of a straight leg extension exercise while seated is the aim of the control law. This exercise is frequently used to treat injuries to the knee and ankle joints that affect the Anterior Cruciate Ligament (ACL). The creation and application of the ankle joint's robotic construction to incorporate it into an exoskeleton for gait rehabilitation is also presented in the paper. It is demonstrated that the suggested control ensures the tracking error's convergence through the creation of the dynamic model and the use of the control algorithm in simulation and experimental tests.

[7] Dongnan Su et al. "Review of adaptive control for stroke lower limb exoskeleton rehabilitation robot based on motion intention recognition" This paper delves into the review of adaptive control techniques applied to stroke patients using lower limb exoskeleton rehabilitation robots, focusing on motion intention recognition. By examining the adaptive control mechanisms employed in these systems, the research sheds light

on enhancing rehabilitation strategies for stroke survivors. The significance lies in improving the effectiveness of exoskeleton-assisted rehabilitation by integrating adaptive control algorithms that cater to the diverse needs of stroke patients, ultimately contributing to the advancement of robotic rehabilitation technologies.

[8] Emma Reznick et al. "Lower-limb kinematics and kinetics during continuously varying human locomotion" The paper presents a comprehensive dataset on lower-limb kinematics and kinetics during various locomotion activities, including walking, running, and stair climbing, across different speeds and inclines. It addresses a significant gap in existing research by including transitions between activities, which are crucial for developing robotic prostheses and exoskeletons that can assist in real-world ambulation. Data were meticulously collected from ten able-bodied participants using a Vicon motion capture system and an instrumented treadmill, ensuring high accuracy in measurements. The study emphasizes the importance of continuous variations in speed and inclination, which are often overlooked in traditional gait analysis. The dataset is structured for easy access and analysis, making it a valuable resource for researchers aiming to enhance the adaptability of assistive devices in human locomotion.

[9] David Pinto-Fernandez et al. "Performance Evaluation of Lower Limb Exoskeletons: A Systematic Review". Study addresses the critical need for benchmarking methodologies in the field of wearable robotic exoskeletons. By analyzing a multitude of research studies focusing on lower limb exoskeleton performance, the paper highlights the dominant emphasis on straight walking evaluations while emphasizing a lack of coverage on essential daily life motor skills. The study identifies a bias towards generic kinematics over human-robot interaction metrics, underscoring the importance of developing practical performance indicators to bridge the gap between research prototypes and market-ready products.

[10] Jubaer Islam Khan et al. "Assistive Exoskeleton for Paralyzed People" The study presents an innovative exoskeleton designed to assist paralyzed individuals in mobility. It utilizes an Arduino-based microcontroller to control the movement of the legs, allowing users to sit, stand, and walk through simple switch commands. The system operates with eight relays that coordinate the actuators for smooth transitions between movements, completing a walking cycle in 18 seconds. Notably, the device is cost-effective, priced at approximately 23,539 BDT, making it significantly cheaper than similar technologies like ReWalk, which costs around 69,000 USD. The prototype aims to enhance the independence of paralyzed individuals, providing both physical support and mobility. Overall, this project showcases a promising advancement in assistive technology for those with mobility impairments.

[11] Ansari Shakir Ahmed et al. "Research Paper on Paralysis Exo-skeleton" The paper presents an innovative approach to exoskeleton design, focusing on rehabilitation for stroke patients through the use of Artificial Pneumatic Muscles (PAM) for actuation. It emphasizes the importance of material selection, advocating for lightweight options like carbon fiber and titanium to enhance efficiency and reduce fatigue during use. The authors compare various actuation systems, highlighting the advantages of pneumatic actuators in mimicking human muscle behavior while conserving energy. Furthermore, the research calls for further exploration into control systems and the potential for full-body exoskeletons, indicating a promising future for this technology in rehabilitation and strength training

[12] Roland Auberger et al. "Smart Passive Exoskeleton for Everyday Use with Lower Limb Paralysis: Design and First Results of Knee Joint Kinetics" The study investigates a novel orthotic system designed to assist individuals with lower limb paralysis in daily activities. It highlights the significant impact of patients' residual muscular functions on joint loads and knee torque, revealing that peak knee power can reach levels comparable to healthy individuals. The findings emphasize the need for robust mechanical designs to accommodate the varying loads experienced by different patients during activities like stair descent and sitting

[13] Bing Chen et al. "A wearable exoskeleton suit for motion assistance to paralysed patients" This study focuses on developing a wearable exoskeleton suit, termed CUHK-EXO, to assist paralysed patients in regaining the ability to stand up/sit down (STS)

and walk. By integrating considerations of ergonomics, user-friendly interface, safety, and comfort, the exoskeleton's mechanical structure, human-machine interface, joint trajectories, and control architecture were designed. Clinical trials confirmed that CUHK-EXO facilitated STS and walking in a paralysed patient, demonstrating effective assistance through accurate joint angle tracking and generated torques. The findings highlight the potential for this exoskeleton to support mobility in individuals with paralysis, showing promise for clinical application.

[14] Lelai Zhou et al. "A human-centered design optimisation technique for robotic exoskeletons based on biomechanical modelling. With an emphasis on human-centered design concepts, this research introduces a design optimisation methodology for robotic exoskeletons using biomechanical simulations. To improve comprehension of actual human-exoskeleton interactions, the method incorporates both exoskeleton simulations and a model of the musculoskeletal system. By simulating an assistive exoskeleton for brachial plexus injury, the study showcases the effectiveness of the proposed methodology in optimizing exoskeleton designs, specifically in determining optimal spring stiffnesses for passive exoskeletons with gravity-compensating capabilities.

[15] N. Aliman, R. Ramli, S. Haris, "Design and development of lower limb exoskeletons: A survey, Robotics and Autonomous Systems". This survey paper explores the design and development of lower limb exoskeletons (LLEs) with a focus on advancements, challenges, and potential applications in augmentation, muscle weakness, and gait recovery. By systematically reviewing multiple joint LLEs, the study addresses key aspects including control strategies, actuators, safety, design considerations such as compactness, noise, weight, cost, natural walking simulation, and power sources. The research aims to shed light on the slow progress of LLE technology and discusses important issues surrounding the design and development of these systems.

8. CONCLUSIONS

Exoskeleton technology has great promise for helping paralysed individuals regain their mobility. Their usefulness keeps getting better thanks to developments in design, actuation, and simulation methods. However, for wider clinical adoption, issues including cost, energy efficiency, and user adaption need to be resolved. To improve accessibility and performance, future studies should concentrate on hybrid actuation and AI-driven control systems.

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