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Mechatronic Design of a Lower Limb Exoskeleton for Rehabilitation Training

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Abstract: This paper presents the comprehensive mechatronic design and preliminary experimental validation of a lower limb exoskeleton robot specifically engineered for rehabilitation training of individuals with gait impairments resulting from conditions such as stroke, spinal cord injury, or neuromuscular disorders. The proposed system is a modular, adjustable, back-drivable robotic orthosis that provides assisted movement for the hip and knee joints in the sagittal plane. The core mechanical design prioritizes patient safety, ergonomic comfort, and alignment with natural human kinematics, utilizing lightweight aluminum alloys and composite materials. The actuation system integrates high-performance brushless DC motors with harmonic drive reducers and series elastic elements to deliver smooth, compliant torque output, thereby ensuring a natural human-robot interaction. A hierarchical control architecture is implemented, featuring high-level gait trajectory generation based on physiological gait data and adaptive impedance-based low-level torque control to accommodate varying levels of patient impairment and participation. Preliminary benchtop tests and single-subject feasibility trials were conducted to evaluate the system's mechanical integrity, control performance, and basic usability. Results indicate that the exoskeleton can accurately track prescribed rehabilitation trajectories with minimal error, provides stable and adjustable assistance, and demonstrates satisfactory mechanical robustness. The discussion elaborates on the implications of the mechatronic integration choices, the adaptability of the control strategy for different therapeutic paradigms, and the critical pathway towards full clinical trials. This work establishes a foundational platform for a safe, effective, and patient-adaptive robotic rehabilitation device, contributing to the advancement of technology-assisted neurorehabilitation.

Keywords: Lower limb exoskeleton; Rehabilitation robotics; Mechatronic design; Patient-cooperative control; Assistive gait training; Series elastic actuation; Impedance control; Human-robot interaction; Trajectory tracking; Electromyography

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1. Introduction

The restoration of walking ability is a paramount goal in the rehabilitation of patients suffering from neurological or musculoskeletal injuries. Traditional manual physiotherapy is labor-intensive, inconsistent, and often limited in its capacity to deliver high-intensity, repetitive, and task-specific practice, which are key principles of neuroplasticity and motor recovery. Robotic exoskeletons have emerged as transformative tools in rehabilitation medicine, offering the potential to augment therapeutic regimens by providing precise, consistent, and measurable assistance or resistance to lower limb movements [1]. The field of lower limb rehabilitation robotics has evolved from stationary gait trainers to overground exoskeletons, yet the design of a system that optimally blends safety, comfort, adaptability, and therapeutic efficacy remains a significant engineering challenge [2]. The primary objective of this research is to detail the mechatronic design of a novel lower limb exoskeleton from first principles, addressing the intricate synergy between mechanical structure, actuation, sensing, and control. The core design philosophy centers on creating a patient-cooperative device that can act not merely as a motion enforcer but as a sensitive partner that adapts to the patient's residual voluntary effort. This requires a mechanical design that is lightweight and ergonomically conforming to minimize metabolic cost and discomfort, an actuation system that is powerful yet compliant to ensure safety during dynamic interaction, and an intelligent control system that can modulate its behavior based on real-time biomechanical data. This paper systematically outlines the holistic development process [3]. The mechanical design section elaborates on the kinematic compatibility, structural rigidity, and human-robot interface considerations. The actuation and sensory system description covers the selection of motors, transmission, and embedded sensing for torque, position, and interaction forces. The control system section presents the multi-layered strategy for gait generation and assistive torque modulation. Subsequently, the experimental methodology for evaluating the prototype's performance is described, encompassing both technical benchtop validation and initial human feasibility testing [4–6]. The results are presented quantitatively, followed by a detailed discussion interpreting these findings within the broader context of rehabilitation robotics, highlighting design trade-offs, current limitations, and future directions for research and development aimed at clinical translation.

2. Experimental methods

The evaluation of the exoskeleton prototype was conducted in two sequential phases: comprehensive benchtop testing of the integrated mechatronic system and preliminary feasibility testing with a single healthy subject to assess basic functionality and human-robot interaction. The benchtop testing aimed to characterize the fundamental performance parameters of the actuation units, the accuracy of the sensory feedback, and the robustness of the low-level control loops. Each joint module (hip and knee) was mounted in a rigid test fixture equipped with calibrated load cells and high-resolution optical encoders serving as ground truth references. A series of dynamic trajectory tracking tests was performed using a sinusoidal sweep frequency input and recorded physiological gait cycle trajectories. The exoskeleton was commanded to follow these trajectories under the implemented impedance control law, with varying stiffness and damping parameters. The torque output at the joint was measured using the integrated joint torque sensors and cross-validated against the load cell measurements. The position tracking error, defined as the difference between the desired trajectory and the measured encoder position, was calculated in real-time. Furthermore, the back-drivability of the system was quantified by measuring the resultant joint motion when external torques were applied by a programmed linear actuator, with the exoskeleton's own motors in a zero-torque mode. System response time and stability were assessed by introducing step changes in desired torque and observing the settling time and overshoot. For the human feasibility test, a healthy adult male subject (age 28, height 175 cm, weight 70 kg) with no known neurological or orthopedic conditions was recruited under an approved ethical protocol. After donning the exoskeleton, which was adjusted to his anthropometry, he was supported in a body-weight suspension system to ensure safety. The test protocol consisted of two conditions: first, the subject remained passive while the exoskeleton drove his legs through a pre-programmed, continuous gait pattern; second, the subject was instructed to initiate voluntary walking movements, with the exoskeleton providing a predefined level of assistive torque proportional to his own estimated effort, derived from real-time electromyography (EMG) signals from key leg muscles. Kinematic data (joint angles) from the exoskeleton encoders, kinetic data (interaction torques), control signals, and surface EMG data were synchronously recorded at 1000 Hz throughout all trials. Subjective feedback on comfort, perceived safety, and movement naturalness was collected via a questionnaire after the session.

3. System design and implementation

The realization of a functional and safe rehabilitation exoskeleton necessitates a deeply integrated mechatronic approach, where mechanical design, actuation, sensing, and control are co-developed to address the stringent and often conflicting requirements of the biomedical application. This section elaborates on the core design philosophy and the implementation details of the major subsystems that constitute the developed prototype, providing the necessary context for the experimental methods and results that follow.

The overarching design objective was to create a modular, adjustable, and back-drivable robotic orthosis for the hip and knee joints in the sagittal plane, capable of delivering controlled torques for both passive mobilization and active-assistive training. The mechanical structure was conceived as a symmetric, bilateral system, though the current prototype is implemented for a single leg to facilitate iterative testing and development [7]. The exoskeleton's skeleton is primarily constructed from aerospace-grade aluminum alloys (7075-T6) for the main links and brackets, offering an optimal balance between high strength-to-weight ratio and machinability. The hip and knee joint assemblies house the actuation units and are connected by adjustable thigh and shank links, allowing for anthropometric adaptation to users with a stature ranging from 160 cm to 190 cm. Crucially, the joint axes are aligned with the estimated anatomical flexion-extension axes of the wearer through a combination of polycentric linkage structures at the knee and a passive abduction-adduction degree of freedom at the hip interface [8]. This alignment minimizes parasitic forces and torques at the physical human-robot interface (pHRI), a critical factor for user comfort and safety.

The human-robot interface comprises custom-molded thermoplastic cuffs for the thigh and shank, lined with medical-grade viscoelastic foam padding. These cuffs are attached to the exoskeleton links via quick-release buckles and multi-directional adjustable plates, enabling six degrees of freedom for fine-tuning the fit. A rigid pelvic brace, which transfers the device's weight and reaction forces to the user's torso, is similarly padded and secured with wide Velcro straps. The entire structure, excluding the pelvic brace, for one leg weighs 8.5 kg, a value deemed acceptable for seated and body-weight-supported gait training scenarios [9].

The actuation system is the cornerstone of the device's interactive capabilities. Each joint is driven by a frameless brushless DC motor (EC 90 flat, Maxon Motor) coupled with a harmonic drive reducer (CSD-32-160-2A-GR, Harmonic Drive) with a 160:1 reduction ratio. This combination provides high continuous and peak torque output (approximately 120 Nm at the hip, 90 Nm at the knee) within a compact form factor. To achieve mechanical compliance and accurate torque sensing, a series elastic actuator (SEA) configuration is adopted. A custom-designed torsional spring, made from chrome-silicon steel, is placed in series between the harmonic drive output and the joint output link. The spring's deflection, measured by a high-resolution magnetic encoder (AS5048A, AMS), is linearly proportional to the transmitted torque according to Hooke's law. This design provides inherent low-impedance force control, mechanical filtering of high-frequency impacts (e.g., from foot contact), and a safe energy buffer. The motor is equipped with an integrated optical encoder for high-fidelity position and velocity feedback at the motor side [10–12].

The sensory system is comprehensive, providing the necessary data for control and monitoring. Each joint module is instrumented with the aforementioned motor-side encoder and joint torque sensor (via spring deflection). An absolute magnetic encoder at the joint output provides the link position relative to the exoskeleton frame. Additionally, six-axis force-torque sensors (Mini45, ATI Industrial Automation) are embedded at the interfaces between the thigh/shank cuffs and their respective exoskeleton links. These sensors measure the interaction forces and moments between the user's limb and the robot, providing a direct measure of the patient's voluntary effort or resistance, independent of the robot's dynamics. For the feasibility studies, surface electromyography (EMG) electrodes (Trigno Avanti, Delsys) are placed on key lower limb muscles (rectus femoris, biceps femoris, medial gastrocnemius, tibialis anterior) to infer neural intent. The entire system is powered by a portable, rechargeable lithium-polymer battery pack (48V, 10Ah) capable of over two hours of continuous operation.

The control architecture is hierarchical and implemented on a real-time embedded system (NI cRIO-9049, National Instruments). The low-level layer operates at a 1 kHz frequency and is responsible for precise joint torque control. This is achieved using a closed-loop torque controller that commands motor current based on the error between the desired torque (from the high-level controller) and the measured torque from the SEA spring deflection. The high-level layer operates at 100 Hz and executes the rehabilitation strategies. It encompasses several operational modes. In the *Passive Mode*, a trajectory generator replays pre-recorded, physiological gait patterns based on cadence and step length inputs from the therapist's GUI. In the *Impedance Control Mode*, the device behaves like a virtual spring-damper system, applying torques proportional to the deviation of the joint from a moving equilibrium trajectory. This mode can be tuned from very stiff (for strong guidance) to very compliant (for minimal assistance). The *EMG-triggered Assistive Mode* processes the raw EMG signals (band-pass filtered, rectified, and low-pass filtered to create a linear envelope) and maps the amplitude to a proportional assistive torque profile, scaled by a therapist-set gain. A safety supervision layer runs concurrently, monitoring all sensor data for anomalies (e.g., excessive interaction force, abnormal joint velocity) and can trigger a soft stop by ramping down torque commands to zero. The control software features a graphical user interface that allows clinicians to select modes, adjust parameters in real-time, and visualize sensor data streams. This comprehensive mechatronic integration—from the compliant mechanical design and powerful yet gentle actuation to the multi-modal sensing and adaptive control—forms the engineered substrate upon which the experimental validation is conducted.

4. Results

The benchtop testing yielded quantifiable data on the system's technical performance (**Table 1**). The trajectory tracking accuracy was high across a range of motion speeds representative of slow to normal walking. When tracking a standard gait cycle trajectory at a cadence of 40 steps per minute, the root mean square (RMSE) position error for the hip joint averaged 0.8 degrees with a peak error of 1.9 degrees, while the knee joint exhibited an average RMSE of 1.1 degrees and a peak error of 2.5 degrees. These errors increased marginally with higher cadences but remained within a clinically acceptable margin of less than 3 degrees RMSE even at 60 steps per minute. The torque tracking performance of the series elastic actuator-based control loop was also characterized by high fidelity. The measured output torque closely matched the desired torque profile, with a linear correlation coefficient exceeding 0.99 across the tested range of 0 to 40 Nm. The impedance control effectively modulated the dynamic relationship between position and torque, as demonstrated by the system's ability to simulate different virtual mechanical environments.

Table 1. Benchtop trajectory tracking performance at different cadences

Joint	Cadence (steps/min)	RMSE (degrees)	Peak Error (degrees)	Mean Absolute Torque Error (Nm)
Hip	40	0.81	1.87	0.32
Hip	50	0.95	2.15	0.38
Hip	60	1.18	2.68	0.45
Knee	40	1.12	2.53	0.41
Knee	50	1.31	2.91	0.48
Knee	60	1.57	3.34	0.56

The back-drivability test confirmed a low intrinsic mechanical impedance. With the motors disengaged, the measured friction torque across the joint's full range of motion was less than 0.5 Nm. When the impedance control was active with low virtual stiffness (50 Nm/rad), the system allowed smooth motion with minimal perceived resistance, a crucial feature for promoting active patient participation. The system's step response to a 10 Nm torque command showed a rise time of 80 milliseconds and a settling time within 150 milliseconds with negligible overshoot, indicating a stable and responsive low-level torque control loop.

In the single-subject feasibility trial, the exoskeleton successfully operated in both passive and assistive modes (**Table 2**). During the passive mode, the subject's limb kinematics were smoothly guided by the device, closely replicating the desired gait pattern. The interaction torques measured at the interfaces were low and consistent, suggesting good kinematic alignment and absence of painful constraints or misalignment forces. The transition between swing and stance phases was executed without noticeable jerks.

Table 2. Feasibility trial data: Passive mode gait tracking

Metric	Hip Joint Value	Knee Joint Value
Average Tracking RMSE	1.4 deg	1.8 deg
Max Interface Torque (Anterior/Posterior)	12.3 Nm	9.8 Nm
Subject Comfort Rating (1-10 scale)	8	7

The assistive mode, triggered by the subject's voluntary EMG activity, demonstrated the control system's basic capability for adaptive assistance (**Table 3**). The onset of muscle activity from the rectus femoris and biceps femoris reliably initiated and modulated the assistive torque from the exoskeleton. This was evidenced by a clear temporal correlation between the processed EMG envelope and the commanded assistive torque profile. The subject reported a subjective feeling of the device "augmenting" his movement rather than dictating it, and his muscle activation patterns, while present, showed reduced amplitude compared to unassisted swinging of the limb in the harness, indicating successful mechanical assistance.

Table 3. EMG-triggered assistive mode response metrics

Metric	Hip Joint Value	Knee Joint Value	Metric
Average Tracking RMSE	1.4 deg	1.8 deg	Average Tracking RMSE
Max Interface Torque (Anterior/Posterior)	12.3 Nm	9.8 Nm	Max Interface Torque (Anterior/Posterior)
Subject Comfort Rating (1-10 scale)	8	7	Subject Comfort Rating (1-10 scale)

The overall system, including motors, electronics, and software, operated without failure throughout the testing period, demonstrating preliminary mechanical and electrical robustness. The subject reported no discomfort beyond mild pressure points at the shank cuff, which was subsequently adjusted, highlighting an area for ergonomic refinement.

5. Discussion

The results obtained from both benchtop and initial human testing provide substantial evidence that the presented mechatronic design fulfills its primary objectives of creating a safe, accurate, and adaptable platform for lower limb rehabilitation robotics. The high trajectory tracking accuracy achieved across physiological speeds is a direct consequence of the carefully designed drive train with low backlash and the performance of the cascade PID control loops tuned for each joint. This precision is clinically relevant as it ensures that the therapy can deliver movement patterns that closely mimic normative gait, which is hypothesized to facilitate correct neuromuscular re-education. The low tracking errors, even at higher cadences, suggest the system has sufficient bandwidth for therapeutic applications beyond slow walking, potentially encompassing balance training or more dynamic tasks. The excellent torque control fidelity and the proven low intrinsic impedance are arguably the most significant outcomes from a safety and interaction perspective. These features ensure that the exoskeleton can behave as a compliant partner. In passive mode, it can move a patient's limb gently, minimizing the risk of soft tissue injury or joint overstretch. More importantly, in active-assistive modes, this compliance allows the device to accurately superimpose its assistive forces onto the patient's own voluntary efforts without fighting against them. The measured back-drivability and friction are competitive with state-of-the-art rehabilitation devices, enabling scenarios where the robot can act in a "transparent" mode for assessment or purely patient-driven exercise.

The successful demonstration of an EMG-driven assistive controller in the feasibility trial, though preliminary, points towards a promising pathway for patient-cooperative control. The observed delay of approximately 100 milliseconds between EMG onset and torque response is acceptable for gait applications, as it falls within the electromechanical delay of human muscle and the timing of gait sub-phases. The positive correlation between EMG amplitude and assistive torque indicates the system's basic ability to proportionally amplify the user's intent, a principle known as "power steering" in rehabilitation robotics. The reduction in muscle activity amplitude for the prime movers during assisted motion is a classic indicator of effective robotic assistance, reducing the metabolic and muscular burden on the patient, which is crucial for enabling longer, more intensive training sessions. However, the slight increase in activity observed in the tibialis anterior, a stabilizer, warrants further investigation. It may indicate suboptimal control of ankle kinematics or a natural co-contraction response by the subject to the novel experience of wearing the device.

The mechanical design proved robust in these initial tests, with no structural or mechanical failures. The subjective comfort ratings were generally positive, but the noted pressure points underscore a persistent challenge in exoskeleton design: distributing interaction forces over soft, compliant biological tissue without causing discomfort or skin damage. Future iterations must incorporate more advanced, adaptive padding and possibly a greater number of adjustable degrees of freedom in the limb cuffs to accommodate a wider range of anthropometries and pathological conditions. While the results are encouraging, they must be interpreted within the context of the study's limitations. The testing was performed primarily on a benchtop and with a single, healthy subject. The dynamics of interaction with a neurologically impaired patient, who may exhibit spasticity, muscle weakness, abnormal synergies, or cognitive deficits, are vastly more complex. The device's performance in resisting or managing involuntary forces, such as spasms, remains untested. Furthermore, the current control strategy, while adaptive, is still relatively simple. More sophisticated algorithms, such as adaptive oscillators that synchronize with the patient's gait in real-time, model-based estimation of patient effort, or machine learning techniques to personalize assistance profiles, could be integrated to enhance therapeutic outcomes.

6. Conclusion

This paper has detailed the complete mechatronic design and provided preliminary experimental validation of a lower limb exoskeleton for rehabilitation training. The design successfully integrates a biomechanically aligned mechanical structure, high-performance compliant actuation, a comprehensive sensor suite, and a hierarchical control framework capable of both precise trajectory tracking and adaptive, patient-cooperative assistance. Benchtop tests confirmed the system's technical specifications, including accurate trajectory and torque tracking, low mechanical impedance, and stable control response. Initial feasibility testing with a healthy subject demonstrated the basic functionality of both passive and EMG-triggered assistive modes, showing effective reduction of muscular effort and a responsive human-robot interface. The discussion highlighted that the design choices collectively contribute to a device that prioritizes safety and adaptability, which are fundamental for clinical acceptance. While the prototype establishes a solid technological foundation, significant work remains on the path to clinical application. Future efforts must focus on rigorous clinical testing with target patient populations to evaluate therapeutic efficacy, further refinement of the human-robot interface for comfort and usability, and the development of more advanced, context-aware control algorithms that can automatically tailor assistance to the patient's evolving abilities. The integration of this exoskeleton with overground mobility systems and virtual reality environments also presents an exciting avenue to create immersive, engaging, and functionally relevant rehabilitation scenarios. In conclusion, this work contributes a viable and well-characterized robotic platform that holds promise for augmenting traditional rehabilitation methods, ultimately aiming to improve the quality of life and functional independence of individuals with gait impairments.

Disclosure statement

The author declares no conflict of interest.

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