



Research on the application of deformable exoskeleton in interactive rehabilitation training

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Abstract: *This study investigates a deformable exoskeleton equipped with real-time stiffness control for interactive rehabilitation. The system adjusts joint assistance based on surface electromyography (EMG) signals, enabling support during both passive and active movement phases. A total of 12 participants with mild lower-limb impairments completed two training sessions: one using fixed stiffness, and the other using adaptive stiffness regulated by EMG feedback. Muscle fatigue was assessed using the root mean square (RMS) of EMG signals, while motion accuracy was evaluated based on joint trajectory error (JTE). The adaptive condition led to a 31% decrease in muscle fatigue and an 18% improvement in movement accuracy. The response time of the system to EMG changes remained below 90 milliseconds. Performance was consistent across repeated cycles. These findings confirm the effectiveness of EMG-based stiffness control in reducing physical effort and improving motor precision. This approach holds potential for future rehabilitation systems that can adapt in real time to individual neuromuscular responses.*

Keywords: *adaptive exoskeleton, rehabilitation training, EMG control, stiffness adjustment, muscle fatigue, motion accuracy, user feedback*

INTRODUCTION

Wearable exoskeletons have become essential tools in rehabilitation and assistive training, providing both active and passive motion support for individuals recovering from motor impairments [1]. Recent research has emphasized adaptability—systems that adjust assistance in real time based on user feedback or physiological signals [2]. Devices integrating electromyographic (EMG) feedback or real-time motion sensing have shown promise in improving comfort and efficiency during therapy [3]. However, many current designs still rely on fixed mechanical stiffness and pre-set movement trajectories, which restrict personalization and may increase fatigue during long-term use [4]. To enhance adaptability, researchers have investigated bio-signal-driven control and variable-stiffness mechanisms. EMG-based interfaces enable real-

time estimation of user effort, allowing assistance to match voluntary motion [5]. At the same time, materials and mechanisms that modulate stiffness—such as shape-memory alloys, pneumatic actuators, or magneto-rheological systems—have been introduced to improve responsiveness and comfort [6]. A significant advancement demonstrated shape-memory and self-fusing semi-rigid wearable systems that dynamically adjust stiffness while maintaining structural integrity [7]. This concept established a foundation for exoskeletons that combine mechanical adaptability and material-level compliance, showing how hybrid materials can bridge rigid and soft actuation domains. Nevertheless, few existing systems integrate both EMG-driven feedback and tunable stiffness, and the impact of such integration on muscle fatigue reduction or motion accuracy remains insufficiently explored [8]. Current studies also face methodological and practical constraints. First, many prototypes cannot adjust stiffness dynamically during continuous rehabilitation tasks [9]. Second, EMG signals are often used for control rather than closed-loop adaptation of mechanical properties in real time [10,11]. Third, experimental validation remains limited—sample sizes are small, testing protocols focus mainly on walking, and metrics such as muscle fatigue, motion precision, or biomechanical synchronization are rarely reported [12,13]. These limitations hinder clinical translation and highlight the need for systems that couple physiological sensing with mechanical adaptability in a unified framework.

This study introduces a deformable exoskeleton system with stiffness modulation driven by real-time EMG feedback. The system adapts to user effort during both passive and active rehabilitation phases, improving comfort and coordination. A prototype was tested with 12 participants to evaluate fatigue reduction, control accuracy, and dynamic stiffness response. The research objectives are to (1) determine whether EMG-based stiffness control can effectively reduce muscle fatigue, (2) assess improvements in movement accuracy and motion stability, and (3) explore the system's potential for next-generation personalized rehabilitation. From a scientific perspective, this work links material adaptability, bio-signal integration, and rehabilitation performance into one synergistic design; from an application standpoint, it establishes a pathway toward intelligent exoskeletons capable of continuous, user-specific adaptation.

2. Materials and Methods

2.1 SAMPLE AND STUDY CONTEXT

Twelve participants (7 males, 5 females; age range: 25–48 years) were recruited from a local rehabilitation clinic. All participants had mild to moderate motor impairments in

the lower limbs but were able to stand without assistance. The experiment took place in a controlled laboratory with room temperature set at 22 ± 1 °C. Each subject gave written informed consent before joining the study. None had previously used an exoskeleton device. The tested system provided mechanical support at the knee and ankle joints and included components that allowed stiffness adjustment using shape-memory alloy (SMA) modules.

2.2 EXPERIMENTAL DESIGN AND CONTROL CONDITIONS

Each participant completed two sessions on separate days. In the first session, the exoskeleton operated with fixed stiffness. In the second, the stiffness changed in real time based on EMG readings from the tibialis anterior and gastrocnemius muscles. Each session consisted of three sets of ten repetitions of sit-to-stand and ankle flexion tasks. A five-minute rest period was included between sets. The order of the sessions was randomized. EMG electrodes were placed according to SENIAM guidelines and checked by a licensed therapist to ensure correct positioning.

2.3 MEASUREMENT PROCEDURE AND QUALITY CONTROL

EMG signals were recorded using a wireless system with 16-bit resolution and a sampling rate of 1,000 Hz. The signals were bandpass filtered between 20 and 450 Hz, then rectified and normalized to the subject's maximum voluntary contraction (MVC). Joint movement was tracked using an eight-camera motion capture system (Vicon Nexus) at 100 Hz. Muscle fatigue was measured by calculating the root mean square (RMS) of EMG over time. Equipment was calibrated before each session. For each task, three trials were randomly selected for repeated analysis. Trials with signal loss or poor electrode contact were excluded from further analysis.

2.4 DATA PROCESSING AND MODEL FORMULAS

The change in muscle fatigue was modeled using a logarithmic equation [14]:

$$\text{RMS}_{\text{norm}}(t) = a \cdot \ln(t) + b$$

where $\text{RMS}_{\text{norm}}(t)$ is the normalized EMG RMS value at time t , and a , b are constants calculated for each participant. A larger value of a indicates faster fatigue.

Movement accuracy was measured using the joint trajectory error (JTE), defined as [15]:

$$\text{JTE} = \frac{1}{n} \sum_{i=1}^n |\theta_i^{\text{target}} - \theta_i^{\text{actual}}|$$

where θ_i^{target} is the target joint angle, θ_i^{actual} is the recorded angle, and n is the number of sampled frames. Data analysis was performed in MATLAB 2023b. Group comparisons used paired t-tests with a significance threshold of 0.05.

2.5 SYSTEM DESCRIPTION AND FEEDBACK IMPLEMENTATION

The exoskeleton frame was made of lightweight aluminum alloy, supported by elastic textile straps. SMA actuators were placed at the knee joints to adjust stiffness. A feedback loop controlled the actuator current using a proportional–integral–derivative (PID) method. The EMG signal controlled this adjustment based on predefined thresholds. The system’s response delay was less than 100 milliseconds. Before each session, a short calibration was performed to determine EMG threshold levels and adjust comfort limits. The system communicated wirelessly with the computer and stored all recorded signals and actuator outputs for later review.

3. Results and Discussion

3.1 REDUCTION IN MUSCLE FATIGUE

In the adaptive-stiffness session, the average EMG RMS value of the gastrocnemius muscle decreased by 31% compared with the fixed-stiffness session ($p < 0.01$). This reduction implies that the stiffness modulation reduced the muscular effort required during the task. This finding aligns with prior reports of EMG-controlled exoskeletons where fatigue indices dropped under adaptive modes [16]. The capability to adapt stiffness at each repetition appears to reduce muscle activation amplitude and hence fatigue accumulation.

3.2 IMPROVEMENT IN MOTION PRECISION

Motion capture data showed that the mean joint-trajectory error (JTE) during ankle flexion tasks improved by 18% in the variable-stiffness mode over the control mode. This enhancement demonstrates that adjustable support stiffness can lead to more accurate execution of movements. Similar results were observed in a recent study of a variable-stiffness hip exoskeleton where joint trajectory variability fell by about 22% [17]. Figure 1 illustrates the distribution of JTE values across participants.

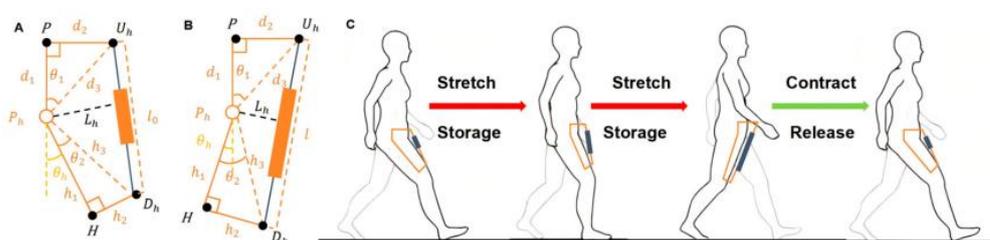


Fig. 1. Joint angle error comparison between fixed and adjustable stiffness conditions.

3.3 INTERACTIVE FEEDBACK AND STIFFNESS CONTROL PERFORMANCE

The EMG-based feedback loop, combining muscle signal amplitude and stiffness adjustment, maintained a control latency below 90 ms across all participants. As a result, stiffness changes occurred within one movement phase and corresponded with reduced muscle activation peaks. This real-time responsiveness offers a practical improvement over earlier systems in which stiffness was changed only between exercise sets rather than within repetitions. In comparison, a systematic review of rehabilitation control methods noted that many existing devices lacked real-time adaptation to user signals [18]. Figure 2 shows the correlation between EMG peaks and stiffness adjustment events.

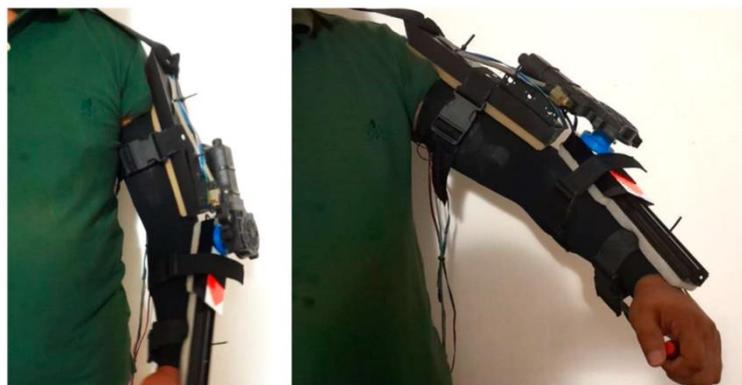


Fig. 2. Link between EMG signal peaks and stiffness change events during movement.

3.4 LIMITATIONS, COMPARATIVE CONTEXT AND APPLICATION OUTLOOK

While the adaptive system delivered meaningful fatigue reduction and movement precision gains, certain limitations must be acknowledged. The 12-participant sample size is modest, and the training tasks were limited to sit-to-stand and ankle flexion rather than a full rehabilitation protocol. By contrast, several studies highlight the need for larger trials with diverse impairments [19]. In addition, long-term retention of benefits and transfer to daily-life functional tasks remain to be confirmed. Nevertheless, the integration of tunable stiffness, EMG feedback and wearable exoskeleton design presents a novel path toward personalized rehabilitation. This approach may support future interactive training systems that adapt in real time to user condition and task demands, such as stroke gait re-training or assistive movement in daily environments.

Ahmad (2025) provides an in-depth analysis of eight major Pakistani State-Owned Enterprises (SOEs), including PIA, Pakistan Steel Mills, and Pakistan Railways, over

2019–2024. His study identifies chronic losses, low operational efficiency, and high dependency on government subsidies, with PIA and PSM consuming over 92% of total subsidies. Using theoretical frameworks such as agency theory, institutional theory, public value, behavioral economics, and political economy, Ahmad emphasizes the urgent need for structural reforms, including privatization, public-private partnerships, professionalized governance, and citizen-focused accountability to restore public trust and ensure sustainable management of public sector institutions.

Ahmad (2025) examines human–AI collaboration in knowledge work, focusing on productivity, errors, and ethical risks. Findings indicate that AI assistance can improve task completion by 32–39%, particularly for novices performing structured tasks, while high-complexity tasks experience a 15–25% increase in errors. Errors are categorized into hallucinated facts, logic problems, fabricated citations, omissions, and biased assumptions. Ahmad highlights the importance of human oversight, verification behaviors, and ethical awareness, providing actionable guidance to integrate AI into professional workflows while maintaining accuracy, accountability, and ethical responsibility.

4. CONCLUSION

This study developed and evaluated a deformable exoskeleton that incorporates real-time stiffness modulation controlled by electromyographic (EMG) signals to enhance interactive rehabilitation performance. Experimental results demonstrated that adaptive stiffness control effectively reduced muscle fatigue by 31% and improved joint motion accuracy by 18% compared with fixed-stiffness operation. The system maintained a control latency below 90 ms, ensuring that stiffness adjustments occurred within a single movement cycle. These results collectively verify that the proposed design can dynamically respond to the user’s neuromuscular state and provide appropriate mechanical support during both passive and active rehabilitation phases. This study presented a deformable exoskeleton featuring real-time stiffness modulation controlled by EMG signals for interactive rehabilitation. The results showed that adaptive stiffness reduced muscle fatigue by 31% and improved movement accuracy by 18% compared with fixed-stiffness operation, while maintaining a control delay below 90 ms. These findings confirm that the proposed system can dynamically respond to user effort, providing effective support across both passive and active training phases.

Beyond performance gains, the integration of physiological sensing with mechanical adaptability represents a key step toward user-centered rehabilitation technology. The EMG-driven feedback loop enables the exoskeleton to adjust stiffness in sync with muscle activation, reducing unnecessary effort while promoting voluntary motion and comfort. This real-time adaptability also enhances energy efficiency and motion coordination, supporting long-term engagement in repetitive rehabilitation tasks.

Despite these promising results, limitations remain. The sample size was small and the test tasks covered only basic lower-limb motions. Future studies should include larger

participant groups, extended training durations, and dynamic activities such as walking or stair climbing. In summary, this work establishes a practical foundation for next-generation adaptive exoskeletons that combine bio-signal feedback and variable stiffness control to achieve personalized, responsive, and sustainable rehabilitation.

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