Multiple Activities Rehabilitation Using Lower-Limb Exoskeletons: A Pilot Study with Two Stroke Patients

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Abstract. Patients with stroke can experience significant gait impairments, limiting their mobility and quality of life. Robotic exoskeletons offer a promising avenue for gait rehabilitation, but simple-to-use and effective control strategies are crucial for clinical settings. This paper presents a pilot study investigating the feasibility and potential benefits of a data-driven impedance control approach for lower-limb exoskeletons in two participants with stroke. Participants underwent a training session with the exoskeleton during which kinematic and EMG data were collected. Preliminary results from these experiments suggest that the data-driven impedance controller was able to provide appropriate assistance during five distinct ambulation modes (level-ground walking, ramp ascent/descent, stair ascent/descent), increasing stride length, foot clearance, reducing gait speed variability, while maintaining the user active in the exoskeleton (similar or higher EMG activation), in comparison to natural walking.

1 Introduction

Rehabilitation robotics has the potential to transform gait therapy for individuals with neurological conditions, enabling personalized, intensive, and engaging interventions. Within this field, lower-limb exoskeletons have emerged as a promising tool, providing partial assistance to encourage voluntary movement and facilitate motor recovery. However, translating the potential of exoskeletons into clinical practice requires control systems that can adapt to the unique gait patterns of each patient, especially those with diverse movement impairments like patients with stroke [1].

J. L. Pons et al. (Eds.): ICNR 2024, BIOSYSROB 31, pp. 218–222, 2025.
https://doi.org/10.1007/978-3-031-77588-8_43

Impedance control, a popular approach in exoskeleton control [2], offers the flexibility to adjust haptic assistance based on individual needs. However, the complexity of tuning multiple interdependent parameters often poses a significant barrier to clinical implementation [1]. Furthermore, the success of assistance hinges on the control system's ability to accurately identify and respond to the nuances of individual gait phases, which can be especially challenging in clinical populations with altered movement patterns.

We propose a three-level control architecture for a lower-limb exoskeleton, leveraging open-source datasets to extract equilibrium angles for different gait states [3]. Building upon this foundation, the present study focuses on the translation of this approach to clinical settings. We present preliminary results and key insights gained from applying this control method with individuals who have experienced a stroke.

2 Methods

2.1 Exoskeleton and Control

A commercially available exoskeleton (ExoMotus-X2, Fourier Intelligence, Singapore), with 4 active (hip and knee) and two passive (ankle) degrees of freedom, was used in this study. The device has been modified as described in [4] and controlled using a state-machine (SM) architecture using impedance control, in which equilibrium angles are based on a benchmark dataset [3]. Following a pilot trial with a first patient, the system was adapted for clinical population by (1) lowering the weight shift threshold to trigger the swing phase (from 80% of the body weight to 70%), (2) increasing knee flexion assistance in swing to address hyper-extension and (3) enabling non-reciprocal gait patterns (i.e., for facilitating stairs navigation). After these changes, our generic parameters set, fine-tuned with healthy individuals, provided comfortable walking for the second participant without further tuning.

2.2 Data Collection

Two individuals with chronic stroke (male, 65 years old, 162.5 cm, 66.7 kg, right paretic side; female, 75 years old, 160 cm, 57 kg, right paretic side), participated in the study. The institutional review board of Northwestern University approved this study (STU00212684). EMG and IMU data were collected using a wireless system (Trigno, Delsys, USA). EMG data from the rectus femoris (RF), biceps femoris (BF), medial gastrocnemius (MG), and tibialis anterior (TA) muscles were collected bilaterally and preprocessed (bandpass 20–400 Hz with a sixth-order Butterworth filter, notch filter 59–61 Hz, low-pass filter 5 Hz) and recorded at 1 kHz. IMU data were collected at 150 Hz. An additional IMU was placed on the back of the patient. This data collection include walking without the exoskeleton (level ground walking, ramps, stairs), followed by an exoskeleton training session. The exoskeleton training included an adaptation phase and subsequent data collection on level ground, ramps, and stairs in 10-min circuits.

3 Results and Discussion

SM control appeared to influence gait kinematics, as evidenced by changes observed in IMU data (Fig. 1). For example, maximum right (paretic) knee flexion angle increased from 34 ± 10[1] degrees without the exoskeleton to 59 ± 17° with SM condition. Additionally, EMG data (Fig. 2) revealed alterations in muscle activation patterns with the SM control. Higher or similar level of activation using the exoskeleton suggests that the user is still active in the SM condition. Moreover, muscles of the paretic (right) side show higher increase than the left side (for e.g., maximum activation of the TA). This suggests the user may be actively engaging the paretic side when using the exoskeleton. These findings indicate that the SM control may promote more challenging and symmetrical gait.

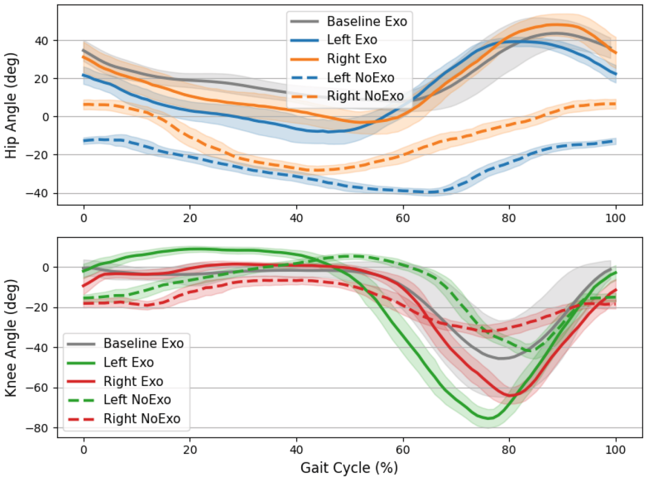

Fig. 1. Hip and knee joint angles in sagittal plane, during level ground walking. Exo and No Exo conditions correspond to one stroke subject, for left and right (paretic) side. Baseline Exo corresponds to left side of 14 individuals without any gait impairment walking with the state machine (assuming symmetry). Shaded area highlights standard deviation.

In this preliminary experiment, the patient demonstrated improvements in stride length and foot clearance while using the exoskeleton in level ground walking. Stride length increased from 0.57 ± 0.074 m without the exoskeleton to 0.80 ± 0.058 m with the exoskeleton, and foot clearance increased from 0.078 ± 0.026 m to 0.16 ± 0.031 m. However, self-selected gait speed slightly decreased from 0.42 ± 0.068 m/s to 0.38 ± 0.029 m/s, which may be attributed to the difficulty of use of the device in general, in addition to the set of parameters used. Similar results were observed in climbing up and down ramps. Stairs are

[1] Results are reported using mean ± standard deviation.

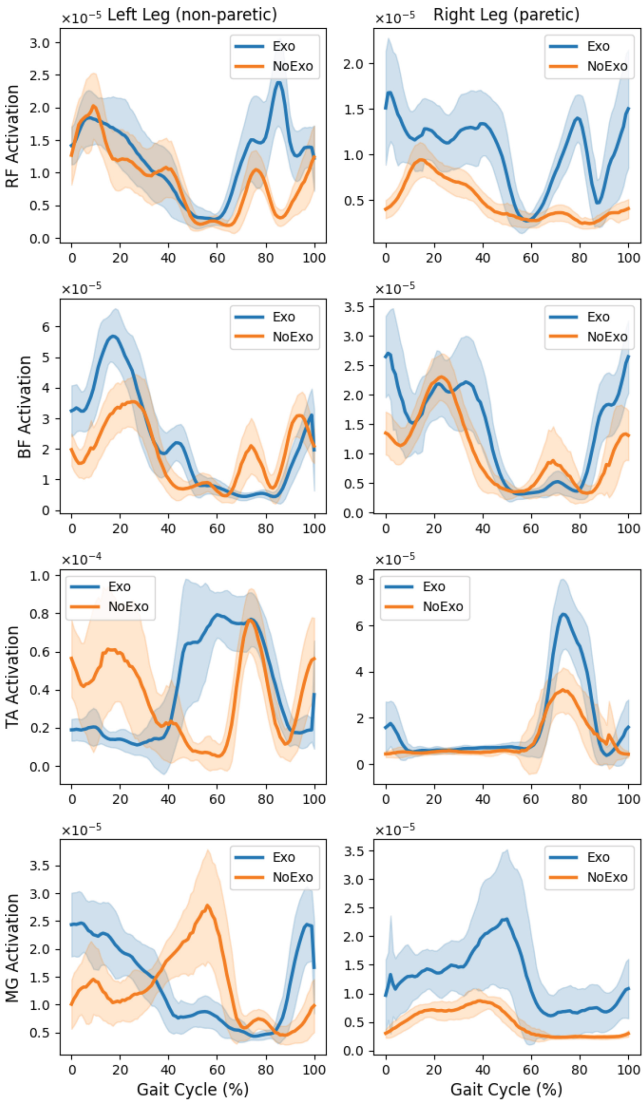

Fig. 2. EMG activities during post-stroke walking of one subject, with and without the exoskeleton. Shaded region corresponds to standard deviation.

still a difficult task for the user with the SM condition, notably because of the limited range of motion of the exoskeleton at the ankle joint.

4 Conclusion

The preliminary results indicate that the proposed state machine-based control architecture holds promise for improving gait in individuals with stroke. The observed increase in stride length and foot clearance, as well as reduced gait speed variability, suggest potential benefits in functional mobility and safety. Future studies should focus on recruiting a larger and more diverse group of patients to validate these initial findings, evaluating the long-term impact of this specific exoskeleton-assisted gait training on functional outcomes, and optimizing the SM control parameters, notably using machine learning techniques, to maximize gait improvement.

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