Personalizing Assistive Wearable Devices Through Passive BCI: A Proof-Of-Concept Study

Morteza Khosrotabar [1], Asghar Mahmoudi[2], Andre Seyfarth[1], and Maziar A. Sharbafi[3]
[1]Lauflabor Locomotion Laboratory, Institute of Sports Science, Technical University Darmstadt, Darmstadt, Germany
[2]Institute for Mechatronic Systems, Faculty of Mechanical Engineering, Technical University Darmstadt, Darmstadt, Germany
[3]Control and Cyber-Physical Systems Laboratory, Technical University of Darmstadt, Darmstadt, Germany
[1] Email: corresponding.author@email-address.com

Summary

This proof-of-concept study demonstrates how EEG-based passive BCIs can help personalize exoskeleton assistance by capturing user-specific preferences in real time. Fourteen participants wore a one-degree-of-freedom knee exoskeleton with adjustable stiffness and performed a sinusoidal knee-swing task, while EEG, EMG, and kinematics were recorded. Subjective difficulty ratings increased in tandem with pneumatic pressure, and the corresponding changes in alpha- and beta-band power revealed the underlying brain responses. Classifiers trained on these EEG features identified exoskeleton settings with 76% accuracy on average, supporting the viability of neuroadaptive control for optimized, user-centric exoskeleton performance.

Introduction

Lower limb exoskeletons can enhance mobility and quality of life, but personalizing their assistance remains challenging [1]. Existing approaches rely on Human-in-the-Loop Optimization or biomechanical models, which face issues like sensor inconsistency and complex neuromuscular dynamics [2]. Recent advances in passive brain-computer interfaces (BCIs) offer an alternative by leveraging brain activity to capture both objective and subjective user experiences [3]. EEG studies reveal how cortical dynamics in motor regions reflect users' adaptive responses to exoskeleton settings [4, 5]. Building on this, our research investigates whether EEG signals can capture user preferences under varying exoskeleton configurations, potentially enabling more user-centric personalization.

Methods

Fourteen participants (23.0 ± 4.1) performed a knee-swing task guided by a sinusoidal visual reference. Each session included 30 trials (Figure 1-a), and a rotary encoder tracked knee angles. Participants wore a one-degree-of-freedom knee exoskeleton powered by a Pneumatic Artificial Muscle (PAM), acting at three randomized pressure levels (1, 3, 6 bar). After each trial, they rated perceived difficulty on a 1–10 scale.

Brain activity was recorded via a 64-channel EEG LiveAmp system (Brain Product, Germany); EMG data were collected from two knee flexors and two knee extensors (Delsys, USA). All signals were synchronized using the Lab Streaming Layer. EEG was preprocessed with the BeMoBIL pipeline, including filtering, interpolation of bad channels, and source reconstruction via AMICA. Eye-related artifacts were removed, and cortical sources were identified based on dipole locations (Figure 1-b) and scalp maps. EEG epochs were defined around knee flexion and extension events, and power spectral density in the delta, theta, alpha, beta, and gamma bands was computed. The RMS of each band served as features in subject-specific classifiers predicting exoskeleton conditions.

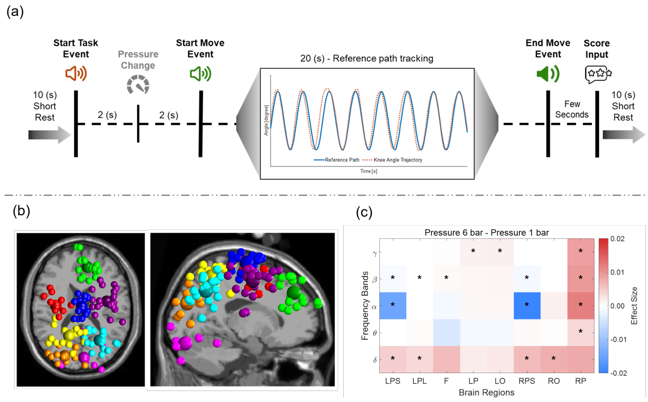

Figure 1: a) Experimental protocol. b) Cortical ICs after group-level post processing. c) Cortical features extracted for training subject-specific classifiers.

Results and Discussion

Participant ratings rose significantly with increasing PAM pressure, as a linear mixed-effects model showed higher perceived difficulty at higher pressures (β = 2.36–5.12, SE = 0.085, $p < 0.001$). EEG power analyses revealed alpha-band desynchronization in bilateral premotor and supplementary motor cortices, and synchronization in the right primary visual cortex (all but delta band). Beta-band modulation was significant in five clusters, and delta power increased in left motor and sensory regions (Figure 1-c). Classifiers trained on these features achieved an average accuracy of 76% across all subjects.

Conclusions

This study demonstrated that varying knee exoskeleton impedance influences user brain activity, which can be detected via EEG. Users perceived these changes, and cortical responses enabled identifying preferred parameter values through a passive BCI. This neuroadaptive approach interprets subconscious user evaluations, reducing cognitive load. These findings pave the way for broader exoskeleton applications, including gait assistance.

Acknowledgments

This work was supported by the Hessian Ministry of Higher Education, Science, Research and Art and its LOEWE Research Priority Program under the Grant "WhiteBox."

References

[1] Slade, P. et al. (2022). *Nature*, **610(7931)**: 277-282.
[2] Zhang, J. et al. (2017). *Science*, **356(6344)**: 1280-1284.
[3] Zander, T. et al. (2016). *PNAS*, **113(52)**: 14898-14903.
[4] Song, S. et al. (2024). *IEEE TNSRE*, **32**: 2522-2532.
[5] Mahmoudi, A. et al. (2025). *IEEE TNSRE*, **33**: 476-487.