PERSONALIZED EXOSKELETON CONTROL FOR OPTIMIZING GAIT ECONOMY IN STROKE SURVIVORS

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Introduction: Stroke survivors often experience impaired gait mechanics and reduced walking economy, which significantly impact their mobility and quality of life [1]. Wearable exoskeletons targeting specific joints, such as the hip and ankle, have shown promise in improving ambulation. Current systems often lack adaptability to individual needs and fail to address real-world challenges, limiting their clinical relevance and user adoption. This study aims at developing personalized exoskeleton systems with end-to-end controllers and Bayesian optimization to reduce metabolic cost and potentially improve gait mechanics for stroke survivors. Our control system for hip exoskeletons uses neural networks to estimate joint moment and power. Scale, delay, and shape parameters were optimized by the Bayesian algorithm to minimize joint positive biological power across all three lower limb joints. By reaching a personalized control paradigm for stroke survivors, we aim to create adaptive systems that support long-term community ambulation.

Methods: We developed a hip joint exoskeleton equipped with a personalized control system based on temporal convolutional neural networks trained with an n=12 dataset collected specifically in stroke survivors, encompassing both paretic and non-paretic legs. The controller uses two neural networks to estimate hip joint torque and hip, knee, and ankle joint power. These power estimates feed into a Bayesian optimization algorithm designed to minimize biological joint positive power by shaping, scaling, and delaying the hip torque estimates, as in figure 1. This deep learning-based control system, designed to mimic human biological movement and introduced in [2], can harmonize control across different locomotion modes, and proved to reduce metabolic cost and joint work compared to operating without an exoskeleton in [3] with device-specific training data. Now, device-agnostic data were used to re-train the TCNs that can potentially be used in different devices, predicting current and future torque values in both paretic and non-paretic limbs. In addition, the second TCN model trained to predict power at all joints serves as a cost function estimator for the Bayesian optimizer. The optimizer identified personalized, optimal scale, delay, and shape parameters for the assistive torque profile for previously collected data (offline).

Results & Discussion: Our personalized control system demonstrated promising results: (i) both TCNs achieved low RMSE values, including joint torque estimates with an RMSE of ~0.15 Nm/kg, and 0.19, 0.26, and 0.34W/kg for joint power at the hip, knee, and ankle respectively, indicating reliable predictions for stroke survivors; (ii) the offline Bayesian optimizer consistently identified high scale factors, low shape factors, and delays between 120–180ms as optimal for minimizing joint positive biological power utilizing offline data collected previously in a limited time frame, consistent with results found in [2]; (iii) expected outcomes: by minimizing positive biological power at the joints, we anticipate reductions in metabolic cost during walking for stroke survivors, although the identified optimal parameters may vary during the human-in-the-loop online optimization. These findings highlight the potential of combining neural networks with Bayesian optimization to create adaptive control systems tailored to individual stroke community ambulators.

Significance: This study represents a step forward in developing personalized exoskeleton technologies for stroke survivors. By leveraging AI-based controllers and optimization algorithms, we can create adaptive systems that enhance gait mechanics while ensuring clinical relevance and user adoption. Future work will focus on real-world testing of both hip and ankle exoskeletons to evaluate their effectiveness in community ambulation settings.

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References: [1] Murray et al. (2007), *Reviews in Clinical Gerontology* 17(4); [2] Molinaro et al. (2024), *Science Robotics* 9; [3] Molinaro et al. (2024), *Nature* 635.

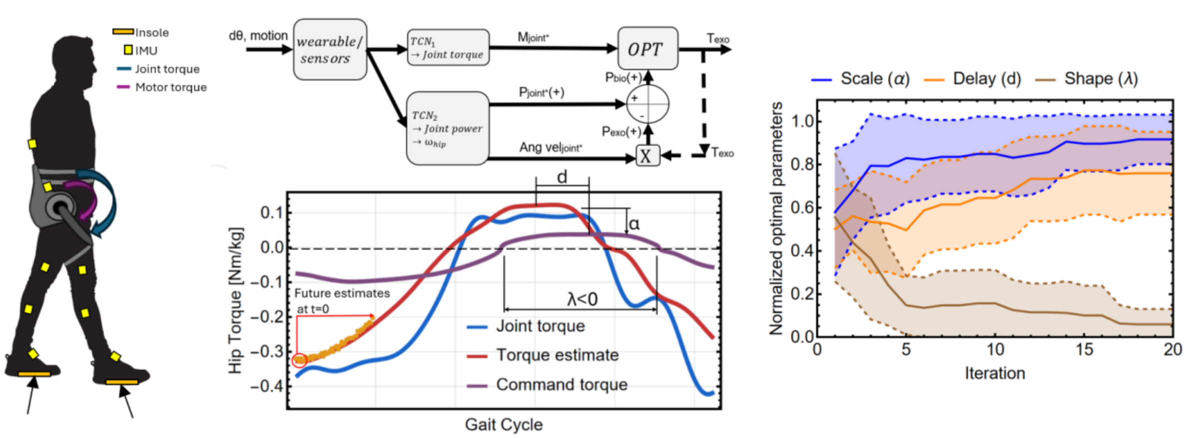

Figure 1: Evolution of the three optimization parameters throughout the optimization process and the resulting command torque versus hip joint torque. Biological work is estimated by subtracting motor power to hip power and integrating over a 25s window utilizing offline data collected previously and assuming unchanged biological power at the knee and ankle joints. Optimization boundaries: α: 0.05-0.3, d: 0-200ms, λ: 0.5-3.