TOWARDS SIMULATION-BASED EXOSKELETON CONTROL DESIGN AND OPTIMIZATION

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Introduction: Developing effective exoskeleton control traditionally requires extensive human subject trials due to the variability of individual responses. Researchers have employed different forms of human-in-the-loop optimization [1,2] and data-driven control [3] to provide effective control to all users, but most approaches demand substantial experimental data, making optimization difficult. Phase-based feedforward ankle exoskeleton controllers have successfully reduced energy expenditure during walking, with previous studies demonstrating up to 40 ± 8% metabolic cost reduction [4]. This method, which parameterizes assistance torque through a spline with four tunable parameters for rise time, peak time, fall time, and peak torque, has been widely adopted. However, evaluating the effects of increasing or reducing spline parameters would require additional human subject experiments, limiting further optimization and investigation. Predictive neuromechanical simulations provide a scalable alternative by modeling natural gait patterns and optimizing control parameters in dynamic environments [5]. Recent advancements in imitation-based musculoskeletal simulations have enabled in-silico evaluation of exoskeleton controllers, reducing reliance on costly human trials [6]. However, the extent to which these simulations can reliably inform exoskeleton control requires further validation. Here, we leverage a MyoSuite-based simulation environment to systematically evaluate phase-based exoskeleton control strategies, determining whether the conventional four-parameter spline is near optimal or if alternative parameter structures offer greater benefits. This study contributes to the broader goal of designing and assessing exoskeleton controllers through simulation by analyzing the trade-offs between controller complexity and effort reduction.

Methods: Simulations were conducted using MyoSuite, a physics-based musculoskeletal simulation framework [7]. A reflex-based neuromechanical model with 22 muscles, 47 control parameters [5], and an ankle exoskeleton were implemented to evaluate exoskeleton control strategies during walking (Figure A). Assistance was applied at the ankle joint using a phase-based controller, with the torque profile defined using a piecewise cubic Hermite interpolating polynomial (PCHIP). Each PCHIP spline is specified by n points, leading to $2 \times n$ parameters, corresponding to the time and magnitude of each point. The four-parameter phase-based spline controller served as the baseline. Eleven parameter configurations will be tested, comparing the baseline four-parameter spline to $n = 1$ through $n = 10$ point splines (Figure B). Optimization is performed using the Covariance Matrix Adaptation Evolution Strategy (CMA-ES), which simultaneously optimizes both musculoskeletal model parameters and exoskeleton control parameters. The primary cost function, *cost of transport*, was calculated as the sum of squared muscle activations normalized by distance travelled and the number of muscles. Each n-point spline condition will be evaluated over five independent trials to ensure robustness. Two additional baseline conditions will be included: one without an exoskeleton and another with the exoskeleton modelled but no active assistance.

Expected Results & Discussion: Varying the number of spline parameters is expected to reveal a trade-off between complexity and effectiveness. While the baseline phase-based controller spline is widely used for its simplicity, it is unlikely to be optimal. Increasing control points should initially improve assistance by better shaping the torque, but these cost reductions are expected to plateau. Moving from three to four or six points may meaningfully reduce effort cost, but excessive parameterization (e.g., 10 points) is unlikely to provide further benefit, while adding unnecessary complexity (Figure C).

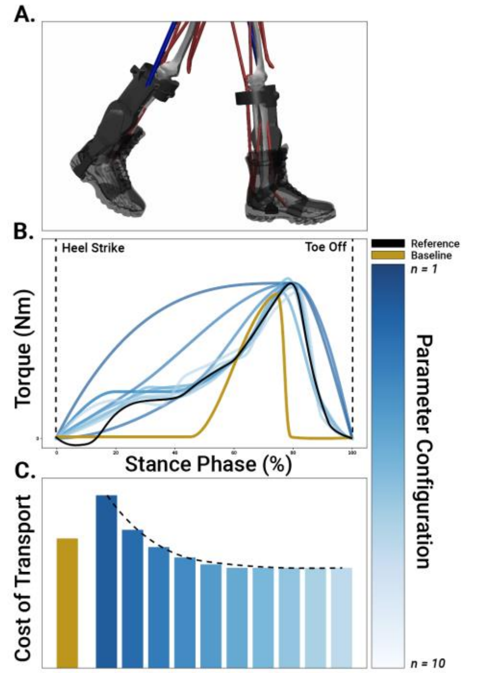

Figure. Neuromechanical model (A), possible spline configurations for each control parameter configuration, (B) and resulting effort cost (C). *Results presented are potential results.*

Significance: Our simulation results will reveal the potential benefits of adding more spline points, enabling us to make better-informed decisions about the relationship between control complexity and cost of transport. By utilizing predictive musculoskeletal simulations, we may reduce the need for extensive human subject testing while providing insights into the optimal balance between controller flexibility and practical implementation.

Acknowledgments: This research is funded by the National Institutes of Health (R00AG065524).

References: [1] J. Zhang *et al.*, *Science*, (2017). [2] Slade, P., Kochenderfer, M. J., Delp, S. L. & Collins, S. H., *Nature* (2022). [3] D. D. Molinaro, I. Kang, and A. J. Young, *Science robotics*, (2024). [4] Poggensee KL, Collins SH., *Science Robotics*, (2021) [5] S. Song and H. Geyer, *The Journal of Physiology*, (2015). [6] S. Luo *et al.*, *Nature*, (2024). [7] Caggiano, V. *et al.*, *PMLR* (2023)