Predictive modeling of human locomotor response to ankle exoskeletons

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Summary

Ankle exoskeletons (exos) can augment human locomotion, but modeling subject-specific responses to exo torques is essential to optimize their design. Existing subject-specific modeling approaches are experimentally cumbersome or contain assumptions that limit model accuracy. We investigated the potential of non-physiological data-driven models to predict response to exo torques during walking in healthy adults. Phase-varying and linear phase-varying models predicted kinematics similar to, and muscle activity better than, a neural network. Phase-varying models of gait may be useful in optimizing exos for individuals with diverse abilities.

Introduction

Optimizing locomotor performance or assisting locomotion using ankle exoskeletons (exos) requires individualized design [1,2]. Research in subject-specific exo design often involves intensive experimental sessions or biologically-based computational models [2,3]. However, experimental approaches generally permit only a small set of outcome measures, and computational models contain assumptions about physiology and motor control that may be invalid for individuals with neurologic impairments. Data-driven modeling paradigms that enable prediction of many outcomes and are free of population-based assumptions may reduce the experimental cost of exo optimization and be step towards optimal exo design beyond resource-rich gait laboratories.

We investigated the potential of three data-driven non-physiological models – phase-varying (PV), linear phase-varying (LPV), and a feedforward neural network (NN) – to predict kinematic and electromyographic (EMG) responses to ankle exo torques during walking in healthy adults. We hypothesized that only the LPV would more accurately predict muscle activity and joint kinematics than the PV model.

Methods

We collected joint kinematic and EMG data from five healthy women (age: 22.8±1.9yr, height: 161.1±8.1cm, mass: 56.3±7.1kg) during treadmill walking at a self-selected speed while wearing bilateral passive ankle exos for four minutes per exo condition. We collected EMG data bilaterally from seven lower-limb muscles. We modulated exo torque by changing the exo dorsiflexion stiffness using three springs (K1-K3) and one zero-stiffness condition (K0) [1].

We first defined a posture-based gait phase, φ, for each exo condition [4]. The PV model ($Y=f_{PV}(\varphi)$) was independent of exo torque and was our baseline model. The LPV model ($Y=A_{LPV}(\varphi)X$) was linear with respect to the states and nonlinear with respect to phase. The NN ($Y=f_{NN}(\varphi, X)$) was nonlinear with respect to phase and states. Inputs, X, consisted of joint kinematics, processed EMG data, exo torque profiles, and their time derivatives at an initial phase, φ, subtracted from the phase-averaged K0 states. Outputs, Y, used the same states at a future phase, $\varphi+\Delta$, where lookahead, Δ, varied from $12.5\leq\Delta\leq100\%$ of a gait cycle. We fit models using the K0, K1, & K3 datasets and validated on K2. We quantified prediction accuracy using relative remaining variance (RRV) and identified differences between models using a Friedman's test with post-hoc Wilcoxon signed-rank tests (α=0.05).

Results and Discussion

The PV (0.30<RRV<0.85), LPV (0.10<RRV<1.00) and NN (0.20<RRV<1.15) explained 10-80% of the variance in the K2 kinematics in most participants (Figure 1). The EMG states were inconsistently predicted for the PV (0.30<RRV<2.50), LPV (0.25<RRV<2.60), implying that the models may not be uniformly useful in predicting EMG across individuals. However, the PV and LPV predictions of EMG were generally more accurate than the NN. The LPV & NN had lower RRVs than the PV model for short lookaheads (Δ<25%) only, suggesting that lookaheads that encompass multiple phases of the gait cycle may not be as well modeled [5].

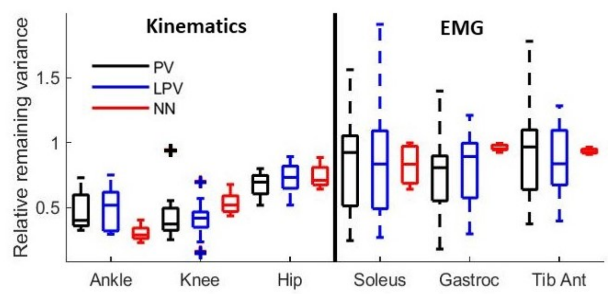

Figure 1: RRVs at the ankle, knee and hip, soleus, gastrocnemius and tibialis anterior for each model for a quarter-gait-cycle lookahead.

Conclusions

The LPV and PV's strong predictive accuracy and clear structure supports further developing models of response to exos. The structure of purely data-driven models may provide insight into principles underlying the heterogeneity of responses to exos in individuals with neurologic impairments.

Acknowledgments

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