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SIMULATING RESPONSE TO ANKLE EXOSKELETONS USING DYNAMIC MODE DECOMPOSITION

Michael C. Rosenberg[1], Keshia M. Peters[1], Makoto Eyre[1] and Katherine M. Steele[1]

[1]Department of Mechanical Engineering, University of Washington, United States
Email: mcrosenb@uw.edu, Web: https://steelelab.me.uw.edu/

INTRODUCTION

Ankle exoskeletons (exos) are used to augment locomotor performance in healthy adults, and to assist and improve locomotion in individuals with motor impairments. However, predicting how a given individual will alter their movement in response to exo assistance remains challenging. Musculoskeletal simulation provides one platform to model subject-specific response to exo properties [1], but model parameters and assumptions about motor control and musculotendon properties are invalid for many individuals [2]. Musculoskeletal models typically use an inverse-dynamic approach, tracking known dynamics to estimate changes in muscle activity, with limited utility to predict changes in kinematics and kinetics. While forward simulations enable synthesis of altered movement, they are computationally expensive and highly sensitive to parameter selection.

Promising experimental approaches have enabled exoskeleton optimization without assumptions about individual physiology and motor control [3]. Low-dimensional biological and phenomenological models provide insight through both their subject-specific dynamical structure and simulated gait patterns [4,5]. However, experimental approaches can be time-consuming, and both experimental and low-dimensional modeling methods are generally specific to a small set of outcomes.

Collectively, the aforementioned models contain attractive characteristics for exo design. An ideal modeling framework to optimize exos for a specific individual would (1) be free of population-average based assumptions, (2) permit simulated response of all states, and (3) generalize across outcome measures.

To address these challenges we investigated the ability of Dynamic Mode Decomposition with Control (DMDc, [6]) to simulate locomotor responses to ankle exo torques. DMDc has been used to model and simulate a range of high-dimensional, complex dynamical systems without governing equations, making it a good fit for our criteria. However, DMDc has not been applied to human gait with exos. The objective of this work was to evaluate the ability of DMDc to simulate locomotor responses to ankle exos and compare to a baseline musculoskeletal modeling paradigm [1]. Specifically, we evaluated a "what-if" experiment, in which we tried to predict kinematic and myoelectric responses to exo torques not used for model fitting. Comparable performance of DMDc to our baseline musculoskeletal simulation would support its development as a predictive tool for exo design.

METHODS

We collected kinematic, kinetic and electromyography (EMG) data from three healthy adults (3F/0M; age: 22.7±2.5yr, height: 156±4cm, mass: 51.4±3.1kg) during treadmill walking at a steady, self-selected speed while wearing bilateral passive ankle exos. We collected EMG data bilaterally from seven lower-limb muscles. We modulated exo plantarflexion torque using three springs (K1-K3) and one zero-stiffness condition (K0). Participants walked for four minutes per condition. We computed joint kinematics in OpenSim 3.3, using a full-body 27 degree-of-freedom model [7].

To capture the nonlinear dynamics of human gait, we defined a hybrid variant of DMDc, which generated unique reduced-order models for different portions of the gait cycle. We defined four models based on phases of the gait cycle (first double-limb support; single-limb support; second double-limb support; swing) within which we expected user-exo dynamics to be approximately constant. DMDc has the structure $x^+ = A_j x + B_j u$, where x^+ is the future system state and A_j & B_j are the state and input matrices, respectively. The subscript, j, denotes the phase of the gait cycle over which the model was built.

We fit the DMDc models using data from the K0, K1 & K3 exo conditions, with joint kinematics, EMG, ground reaction forces and centers of pressure as states, x, and exo torque profiles as inputs, u. States were subtracted from the K0 average gait cycle to reflect deviation from the "unforced" condition, demeaned and scaled to unit variance of the training set. We simulated walking for ten gait cycles from the state at 0% of each gait cycle of the K2 dataset for validation.

As a biologically-based baseline model, we simulated the same ten gait cycles in OpenSim 3.3 using a full-body model with passive exos at the ankles [1,7]. We simulated walking using OpenSim's Static Optimization algorithm to estimate muscle activity for the model's 80 musculotendon actuators. We simulated the K0 condition, and then the K2 stiffness using K3 kinematics and kinetics (the most similar part of our training set to the K2 data), since inverse algorithms cannot predict altered kinematics [1].

We compared the accuracy of the simulated muscle activity and kinematics using the relative remaining variance (RRV) of simulated versus experimental waveforms for DMDc and OpenSim. OpenSim results were transformed to reflect deviation from the K0 condition.

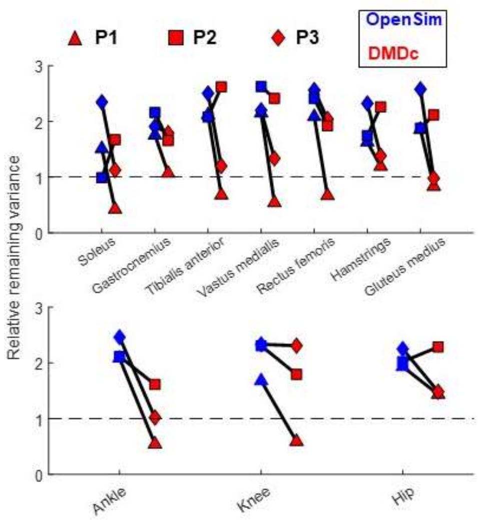

Fig 1: RRV values averaged over the right and left legs for simulated muscle activity (top) and kinematics (bottom).

RESULTS AND DISCUSSION

OpenSim and DMDc had similar fidelity in predicting changes in muscle activity with ankle exos, although DMDc often had slightly better performance (lower RRV for DMDc vs OpenSim, Fig. 1). However, variation existed in the ability of both algorithms to predict changes in muscle activity. On average, DMDc produced RRVs 0.62 less than OpenSim for the plantarflexors, 0.85 for the knee extensors and 0.54 for the hip extensors. Only P1 had RRV values below one, indicating that DMDc captured some of the variance in the experimental data. DMDc explained 60% of the variance in P1's soleus activity ($RRV \geq 0.40$), comparable to a similar modeling approach for running kinematics [4].

DMDc's simulated kinematics were more similar to the experimental data (K2) than the most-similar exo stiffness level (K3). Compared to the average K3 trial, DMDc reduced RRVs on average by 1.16, 0.54 and 0.33 at the ankle, knee, and hip, respectively. Again, P1's kinematics were most accurately predicted, possibly due to relatively large and repeatable responses to exo torque (Fig. 2). We expect that DMDc's predictive accuracy will further improve as kinematics and kinetics vary more between experimental exo conditions. This may be an important consideration when collecting datasets rich enough for parameter estimation within many modeling paradigms [3].

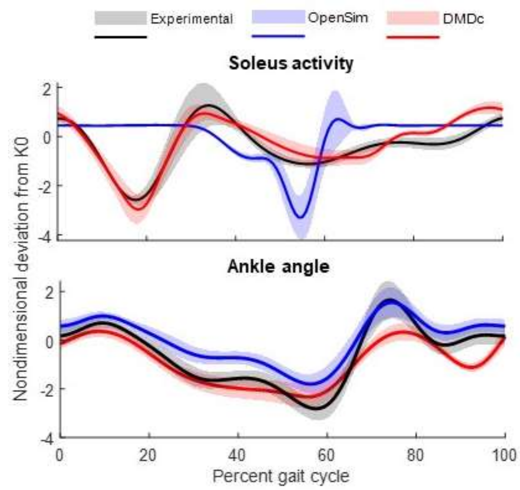

Fig 2: Simulated soleus activity (top) and ankle kinematics (bottom) in OpenSim and DMDc for P1. OpenSim ankle kinematics were from the K3 trial.

CONCLUSIONS

DMDc generated similar or more accurate predictions of locomotor response to exos than our baseline OpenSim model, without any assumptions about individual physiology or motor control. While well-tuned biologically-based models may provide improved predictions, modeling paradigms that relax biological assumptions about response to exo torques may produce more generalizable predictive simulations across individuals with diverse motor abilities. Additionally, the flexibility of such models may enable them to inform exo design beyond resource-rich gait labs.

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