Predictive Gait Simulations of Human Energy Optimization

Anne D. Koelewijn
Machine Learning and Data Analytics Lab, Faculty of Engineering
Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU)
Erlangen, Germany
anne.koelewijn@fau.de

Jessica C. Selinger
School of Kinesiology and Health Studies
Queen's University
Kingston, Canada
j.selinger@queensu.ca

I. INTRODUCTION

Humans can adapt their gait to continuously optimize energetic cost in real-time. We have previously demonstrated this using robotic exoskeletons to shift people's energetically optimal step frequency to frequencies higher and lower than normally preferred [1]. In response, we found that subjects adapted their step frequency to converge on the new energetic optima within minutes and in response to relatively small savings in cost. However, how the nervous system actually performs this optimization in real-time—navigating an expanse of possible movements to arrive at the optimal coordination—is largely unknown. Here, we aim to re-create our experimental paradigm, where added torques at the knee alter the preferred and energy optimal gait, using predictive gait simulations. This modeling testbed will allow us to probe mechanisms underlying the energy optimization of gait—generating predictions of human behaviour and insight into aspects of optimization that are inherently difficult to investigate experimentally.

II. METHODS

A. Musculoskeletal and Exoskeleton Models

We used a sagittal plane nine-degree of freedom musculoskeletal model of the lower limb [2]. We then added an ideal, massless, exoskeleton to our simulations by applying torques at the knee joints that resist both knee flexion and extension, and therefore added an energetic penalty. To replicate the control of the real-world exoskeleton, we made the average resistive torque throughout the stride proportional or inversely proportional to step frequency (penalize-high and penalize-low controller conditions, respectively), the within stride torque proportional to knee angular velocity, and the maximum allowable torque 12 Nm.

B. Energy Optimal Gait Simulations

We generated muscle-driven simulations of walking at 1.3 m/s by optimizing an objective that highly weighted effort minimization (cubed muscle activation) over error minimization (tracking of joint angles and ground reaction forces) with an effort/error weighting ratio of 1000:1. Removing error entirely from the objective function led to kinematically unrealistic gaits. Details of the optimization procedure are given in [2]. We generated walking simulations for each of the three exoskeleton controller conditions, where step frequency was free and included in the optimization. Next, we generated simulations at a range of fixed step frequencies (-20% to +20% of natural preferred step frequency, at increments of 1%) for three conditions: exoskeleton controller on penalize-high, exoskeleton controller on penalize-low, and exoskeleton controller off, natural walking.

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III. RESULTS

Our simulated exoskeleton torques, both throughout the stride and averaged over the stride, resembled that from human experiments (Fig. 1AB). These torques produced changes in simulated effort that were consistent with our experimental energy landscapes; the optimal step frequency shifted to lower and higher frequencies for the penalize-high and penalize-low conditions, respectively (Fig. 1C). When step frequency was included in the optimization, we found distinct gaits for each condition with changes in step frequency toward the optima.

IV. DISCUSSION

Using predictive gait simulations, we re-created our experimental paradigm where exoskeletons are used to alter preferred and energy optimal gaits. In simulation we were able to: replicate the exoskeleton torque applied at the knee joint during gait, produce effort landscapes with optima at high and low step frequencies, and solve for optimal gaits through adaptations in step frequency. Using this modeling testbed, we can now investigate aspects of optimization that are difficult to test experimentally. For example, we can systematically alter the weighting of objectives to predict the effect on gait adaptation. We can also explore what particular kinematics of gait or muscles are driving whole body changes in energy expenditure, offering insight into strategies for improved exoskeleton control.

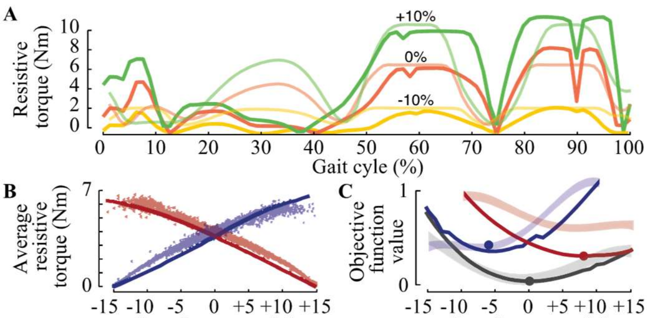

Fig. 1. A. Torques throughout the gait cycle for the penalize-high condition at -10%, 0% and +10% of natural step frequency. B. Average torques across the gait cycle for the penalize-high (blue) and penalize-low (red) conditions. C. Objective function landscapes for the penalize-high (blue), penalize-low (red), and natural (grey) conditions. Circles indicate optimal gaits for each condition. In all plots, solid lines are simulated data and faded are experimental data [1].

REFERENCES

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