Sensory Feedback Synergy Control for Predictive Simulation of Walking

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I. Introduction

Numerous studies have suggested that walking is controlled by a low-dimensional set of muscle synergies. Each muscle synergy is composed of a single time-varying synergy control and a set of synergy weights that defines how the control contributes to the activation of each muscle. Previous studies have implicitly assumed that time-varying synergy controls are generated via a pure feedforward control strategy. No study to date has investigated whether an experimentally measured walking motion could theoretically be produced by synergy controls generated via a pure sensory feedback control strategy.

This study evaluates whether time-varying synergy controls generated using only sensory feedback information are theoretically capable of reproducing an experimentally measured three-dimensional walking motion.

II. Methods

A. *Neuromusculoskeletal Model Personalization*

Walking data collected from a single male subject post-stroke who exhibited only minor hemiparesis were used to personalize a full-body neuromusculoskeletal for the subject. Personalization involved calibrating via optimization the parameters of four model elements: 1) a lower-body kinematic model, 2) a lower-body EMG-driven model, 3) a foot-ground contact model, and 4) a synergy control model utilizing five synergies per leg. Model personalization was performed using walking data collected at the subject's self-selected speed of 0.5 m/s. The personalization optimization process produced a dynamically consistent three-dimensional walking motion controlled by five muscle synergies per leg and that closely reproduced the subject's experimental joint angles, ground reactions, joint moments, and muscle activations for a representative walking cycle (see [1] for further details).

B. *Sensory Feedback Synergy Control Model*

A sensory feedback synergy control model was constructed by fitting the 10 time-varying synergy controls (SC) found by model personalization as a function of lower body joint angles and velocities (akin to muscle spindle feedback) and ground reaction forces (akin to proprioceptive feedback) from the same leg. A prediction optimization was developed using direct collocation optimal control [2] were no feedforward controls were included. Rather, synergy controls were constructed entirely from the sensory feedback model using the calibrated feedback gains and synergy weights. Thus, the prediction optimization varied only the model state to find a dynamically consistent walking motion that was near-periodic.

$$\begin{bmatrix} SC_1 \\ SC_2 \\ \vdots \\ SC_t \end{bmatrix} = \begin{bmatrix} \theta_{1,1} & \theta_{1,2} & \cdots & \theta_{1,n} & \dot{\theta}_{1,1} & \dot{\theta}_{1,2} & \cdots & \dot{\theta}_{1,n} & F_{x_1} & F_{y_1} & F_{z_1} \\ \theta_{2,1} & \theta_{2,2} & \cdots & \theta_{2,n} & \dot{\theta}_{2,1} & \dot{\theta}_{2,2} & \cdots & \dot{\theta}_{2,n} & F_{x_2} & F_{y_2} & F_{z_2} \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots \\ \theta_{t,1} & \theta_{t,2} & \cdots & \theta_{t,n} & \dot{\theta}_{t,1} & \dot{\theta}_{t,2} & \cdots & \dot{\theta}_{t,n} & F_{x_t} & F_{y_t} & F_{z_t} \end{bmatrix} \begin{bmatrix} b_{\theta_1} \\ b_{\theta_2} \\ \vdots \\ b_{F_z} \end{bmatrix}$$

III. Results & Discussion

The joint angles and moments generated by the prediction optimization were compared to those found by the personalization optimization. Even though the prediction optimization did not track any experimental data, it closely reproduced the joint angles and moments from the personalization optimization (Fig. 1). The average RMS error was 0.78 deg for joint angles and 2.21 Nm for joint moments.

The present study demonstrated that synergy controls generated entirely from sensory feedback information are theoretically capable of predicting an experimentally measured walking motion. At least one experimental study has reported that synergy controls are influenced by sensory feedback information [3]. However, when sensory feedback was eliminated, synergy controls were still present, though altered [3]. Thus, a future study will explore the extent to which feedforward versus feedback mechanisms may contribute to the formation of synergy controls.

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References

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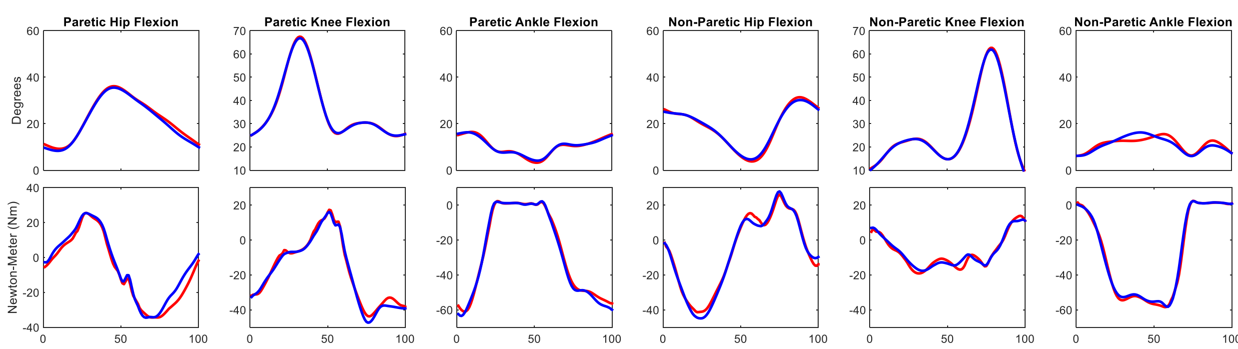

Fig. 1. Comparison of simulated walking data using feedforward synergy controls in a calibration optimization (blue curves) and feedback synergy controls in a prediction optimization. *Top Row:* Simulated joint angle comparison. *Botton Row*: Simulated joint moment comparison.