Human Feedback Control to Maintain Trajectories of Task-Relevant Variables During Sit-to-Stand Motion

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I. INTRODUCTION

Humans rely on feedback mechanisms during locomotion to recover from deviations from a planned trajectory. Models of these feedback mechanisms can inform the design of controllers for assistive devices to ensure compatibility with natural human mechanisms for postural control. Furthermore, models of feedback enable reachability analyses on human movements that provide estimates of stability [1].

Previous state feedback models describe how standing humans maintain balance when perturbed [2] [3]. However, it is unclear whether state feedback models apply to dynamic movements, such as the Sit-To-Stand (STS) motion. A feedback model of STS would provide a useful diagnostic test, since STS instability is strongly correlated with fall risk in older adults [4]. We conducted a perturbative STS experiment, described in Section III, to validate state feedback control laws for dynamic models of STS. We also performed a motor equivalence analysis to determine the task-relevant variables of the STS motion. Section IV relays the results of this analysis and its implementation in the feedback model.

II. BACKGROUND

While feedforward models of human motion may be constructed from observed nominal behavior, models of feedback require observing a response to perturbation. Although it is possible that humans use a full-state feedback controller to stabilize their motions, it may be more efficient to prioritize feedback for a subset of features.

The concept of motor equivalence asserts that jointed bodies respond to perturbation with configurations that maintain the nominal trajectories of task variables [5] [6]. Previous studies in motor equivalence have identified both the horizontal position of a subject's head and the horizontal position of a subject's center of mass (COM) as important task variables during STS [7]. The results of our motor equivalence analysis confirm this finding and provide further characterization of the feedback employed by humans to recover from direct perturbations during STS.

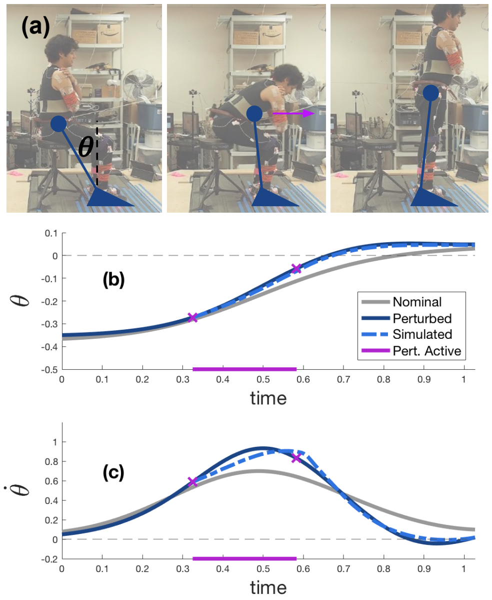

Fig. 1: (a) STS motion modeled as an inverted pendulum. The purple arrow in the middle figure represents a perturbation applied via a cable pull. (b and c) Simulated and observed trajectories of angular position and velocity under perturbation, compared to the nominal trajectory. The purple lines indicate the time interval that the perturbation was applied.

III. METHODS

A. Experiment

Motion capture and force plate data were collected from eleven subjects as they performed the STS task[1]. First, each subject stood from a comfortable seated position five times. The trials were averaged over time to construct a nominal trajectory for each individual. To perturb the initial condition, the subject moved their feet further forward from a nominal foot position for each STS until failure, and then further backward until failure. For a dynamic perturbation, the subject returned to the nominal foot position, and motor-driven cables attached to the subject's waist pulled the subject either forwards or backwards during their motion. Each subject was perturbed with three forward and three backward pulls in a randomized order, and transducers were used to measure the force of each perturbation.

B. Modeling

We model the STS motion using a single inverted pendulum model (IPM) as shown in Fig. 1, and a triple inverted

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[1] All experimental protocols were approved by University of Michigan Institutional Review Board

pendulum model (TPM). Both are dynamic models of the form

$$\begin{aligned} \dot{x} &= f_{\phi}(t,x) + g_{\phi}(t,x)u(t,x) \\ x &\in [\underline{x},\overline{x}] \subset \mathbb{R}^n \\ u &\in [\underline{u},\overline{u}] \subset \mathbb{R}^m \end{aligned} \tag{1}$$

where x represents the state of the model, f and g describe how the torque input u affects the dynamics, and ϕ represents the subject-specific parameters of the model. The state bounds, input bounds, and physical parameters are unique to each individual.

C. Motor Equivalence

Using the perturbative experimental data and the TPM, we projected changes in joint configurations into motor equivalent (ME) and non-motor equivalent (NME) subspaces of the joint configuration space for eight candidate task variables.

The ME subspace is the nullspace of the Jacobian that relates changes in joint configuration to changes in the task variable at each point in time, and the NME subspace is the orthogonal complement of the ME subspace. We project the residual of the perturbed joint trajectories, with respect to the nominal trajectory, into the two subspaces. Large ratios of ME:NME projection magnitudes indicate that the joint configuration response to perturbation preserves the trajectory of the task variable.

D. Control Law Modeling

Control laws were developed for each subject's IPM. First, a feedforward (FF) component was computed by running an optimal control program to determine an input that closely replicated the subject's nominal trajectory. Then, an LQR algorithm was run about a linearization of the subject's nominal COM trajectory to determine the time-varying state feedback gains that minimized error from the nominal trajectory, with a small cost on control input. The feedforward and feedback terms added together (FF+FB) were used to model human postural control of the STS motion.

E. Validation

We computed the L^2 error between the simulated and observed trajectories to validate our models using both the FF and FF+FB controllers. For the foot-shifted perturbation, the angle associated with the initial foot position was the initial condition for the simulations. The cable pull perturbation was simulated by adding an approximation of the applied force into the model after the onset of perturbation.

IV. RESULTS

The x-position of the COM and the x-position of the head showed the greatest ME:NME ratio, and are therefore the most likely to be task variables (Fig. 2). The IPM simulations with FF+FB closely match the human response to initial condition and dynamic perturbations (Fig. 1). The error between the observed and simulated FF+FB response is similar in magnitude to the maximum intertrial error between an individual's nominal STS motions. The simulations with FF alone do not reflect the observed response to large perturbations in the initial condition, nor dynamic perturbations.

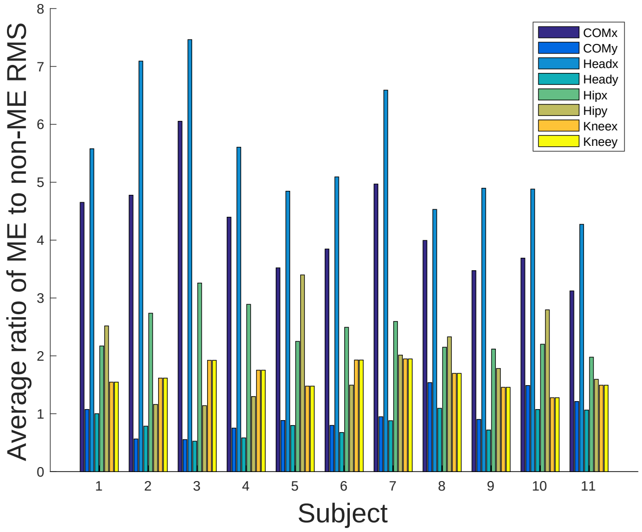

Fig. 2: Ratio of each subject's averaged root mean square (RMS) values for the magnitudes of the motor equivalent (ME) and non-motor equivalent (NME) projections over time with respect to eight candidate task variables. Large ratios of ME:NME projection magnitude indicate that the task variable in question was preserved during perturbation.

V. DISCUSSION

By examining human response to perturbation, we show that a model with state feedback effectively simulates the control strategy humans use to correct for deviations during the dynamic STS motion. We will use the results from motor equivalence analysis to apply feedback about the task-relevant variables in the TPM. Such analysis will reveal whether the added complexities in the TPM are significantly more informative for characterizing the human response to perturbation during STS.

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