Toward Balance Recovery with Active Leg Prostheses Using Neuromuscular Model Control

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Abstract We seek to improve balance recovery in amputee gait by taking advantage of the advent of active leg prostheses. Toward this goal, we use inspiration from biology to identify reflex-like control strategies that stabilize gait, refine these strategies in simulations of amputee locomotion, and evaluate the resulting controllers in experiments with human subjects wearing custom prototypes of active leg prostheses. Our results so far indicate that reflex-like control can improve balance recovery over existing control strategies used in active leg prostheses. However, further research on the hardware realization of the control is needed to more rigorously evaluate its potential benefit to amputee locomotion.

1 Introduction

In the past, research on prosthetic legs has focused on improving the energetics of amputee locomotion. With the advent of active prosthetics, the focus is shifting toward increasing the stability and robustness of amputee gait. This is a timely development. Lower limb amputees remain at high risk of falling as the leg prostheses currently on the market provide only limited functionality for recovering balance from gait perturbations such as slips, trips and pushes [1].

One approach to improving balance recovery with active leg prostheses is to explore human-like limb controls. When humans and other animals walk or run, they rely on a hierarchical controller structure. Specifically, the individual limbs are controlled at the lowest level of this hierarchy by neural circuits residing in the spinal

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cord. Although higher level, central inputs are necessary for complex behavior, the spinal limb control suffices to generate locomotion [2]. Understanding and mimicking the function of the limb controller could thus reveal decentralized control templates for active prostheses, including for the recovery of balance after gait perturbations.

We pursue this bio-inspired control approach and here present our progress toward improving balance recovery with active leg prostheses.

2 Methods and Results

2.1 Bio-Inspired Control of Balance Recovery

We extract fundamental gait control strategies by studying conceptual models of the stance and swing leg mechanics. For balance recovery in particular, we focused on swing leg placement, which is critical for gait stability [3]. We investigated a double-pendulum model of the swing leg and identified a control that takes advantage of segment interaction dynamics to achieve robust leg placement under large disturbances while generating trajectories and joint torque patterns similar to those patterns observed in human walking and running [4] (Fig. 1a). We subsequently interpreted this control within a musculoskeletal model of the human leg in swing using physiologically plausible spinal reflexes [5] (Fig. 1b). In general, these spinal reflexes are equivalent to feedback control loops, which can serve as decentralized control templates for robust leg placement in artificial limbs.

2.2 Verification in Amputee Simulation

In a subsequent stage, we use a neuromuscular control model of human locomotion to evaluate proposed control strategies [6]. For the derivation of prosthesis control strategies, we adapted this model to amputee gait with a unilateral powered knee-and-

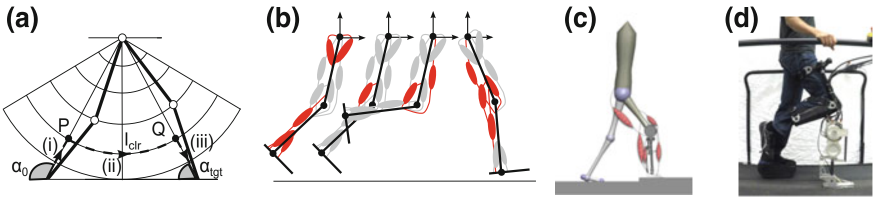

Fig. 1 Stages of progress on balance recovery with active prostheses. **a** Conceptual double pendulum model and control for robust swing leg placement. **b** Interpretation of control with decentralized muscle reflexes. **c** Verification in amputee simulations. **d** Preliminary test of control with active knee prosthesis (passive ankle)

ankle prosthesis (Fig. 1c). Comparing the proposed decentralized feedback control with the state-of-art impedance control used in active leg prostheses [7], we found that the proposed control recovers from larger disturbances, including unexpected ground height changes, swing leg trips, and pushes to the body [8]. These results suggest the proposed control to improve the balance recovery in amputee gait over existing control strategies.

2.3 Prosthesis Hardware Experiments

Finally, we develop prototypes of active prostheses and test new control strategies in experiments with human subjects. At the current stage of progress, we have designed and built an active knee prosthesis connected to a passive ankle unit (Fig. 1d). In initial hardware experiments with one non-amputee user wearing this prototype via a crutch, we have found that the proposed reflex control effectively handles disturbances in early and late swing, but fails to avert falls for mid-swing disturbances [8].

3 Discussion and Conclusions

We took inspiration from how humans and animals control locomotion and identified a decentralized control for increasing the robustness and stability of gait. We then translated this control into a controller for active leg prostheses. In amputee simulations, we observed the control improves balance recovery after unexpected disturbances. However, the initial hardware experiments show that while a promising alternative, the proposed prosthesis control requires further research to successfully transfer it to amputee gait.

Our current efforts in this direction include completing the active knee-and-ankle prototype prosthesis, refining the control to successfully handle mid-swing disturbances, and evaluating the proposed control against state-of-art controls in amputee experiments. We believe this research will, over time, lead to active leg prostheses that help increase stability and robustness in amputee locomotion. Ultimately, this research may also evolve toward integrated human robot systems in which neural interfaces communicate with the active leg prostheses in ways similar to how the supraspinal part of the nervous system communicates with the spinal limb controllers in humans.

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