

Title. From Machine to Biomimetic Control of Powered Prosthetic Legs

Motivation. In this talk I will present my ongoing work at the Center for Bionic Medicine of the Rehabilitation Institute of Chicago, where I am translating theoretical control approaches from robot walking into biomimetic control strategies for powered prosthetic legs. Estimates indicate that by 2050 the U.S. will incur a two-fold increase in the incidence of amputation, due in large part to the prevalence of cardiovascular disease (Ziegler-Graham et al., 2008). Current prostheses do not automatically adapt to shoe differences (e.g., heel height), environmental conditions (e.g., ground slope), or external forces, which cause instability and discomfort for their users. High-performance prostheses could significantly improve the quality of life for over 600,000 lower-limb amputees in the U.S., whose ambulation is slower, more asymmetric, less stable, and requires more energy than able-bodied individuals.

State of the Art. Modern prosthetic legs have mechanically passive joints that mimic human joint resistance to angular velocity (i.e., viscous damping). This biomimetic approach fails to replicate the ability of human muscles to generate large amounts of mechanical power, which is why amputees typically struggle to climb inclines and stairs. The recent advent of mechanically powered legs presents new opportunities and challenges in prosthetic control systems. Most powered legs (e.g., the PowerKnee) offer no more than a simple extension of the traditional control paradigm, where viscosity and stiffness (known together as impedance) change based on the time from heel strike. The iWalk ankle switches between several impedance and muscle reflex models based on sequential events during the gait cycle (Eilenberg et al., 2010). These prostheses have multiple control models that must be manually tuned for each user, task, and environment, and their time-varying strategies are not necessarily robust to external perturbations that push joint kinematics (i.e., angles and velocities) forward or backward in the gait cycle. These limitations could potentially be addressed by a unifying control model based on a concept from dynamics and control theory known as phase (i.e., the location in an oscillation). Prosthetic control would greatly benefit from a mechanical representation of the gait cycle phase, which could be continuously sensed by a prosthesis to match the body's progression through the cycle. Central to this control challenge is a fundamental gap in knowledge about how the human nervous system maintains a sense of phase and subsequently controls joint motion during walking.

Approach. The field of autonomous walking robots provides a source of non-biological methods, specifically founded in mathematical modeling and control theory, for designing novel control strategies for wearable robots. Among innovations in the field are feedback controllers that produce joint torques to enforce “virtual” kinematic constraints. These constraints define desired joint patterns as functions of a mechanical phase variable (e.g., the stance leg angle). This control concept has proven successful in experimental bipedal robots such as RABBIT and MABEL (Westervelt et al., 2007). Biomimetic kinematic constraints and a biomechanical phase variable could potentially make prosthetic legs more robust and easily tuned than the biomimetic approaches used in prostheses to date.

These theoretical control methods inspire my hypothesis that the progression of human joint patterns is driven by the location of the center of pressure (COP)—the point on the foot sole where humans support their body weight against the ground. Hansen and Wang (2010) recently showed that during human locomotion, geometric relationships exist between stance leg joints and the COP. When the trajectory of the COP is examined relative to the tibia, it is found that the ankle and the foot together conform to a circular rocker shape (coined “rollover shape” by Hansen) that is invariant over walking speeds, heel heights, and body weights. I have shown that this geometric relationship corresponds to a kinematic constraint between the COP and leg joint angles. The fact that the COP moves monotonically from heel to toe during steady gait suggests that the COP is a human phase variable. Mimicking this behavior on a prosthetic leg could allow systematic adaptation that cannot be achieved when simply tracking able-bodied human data (e.g., from level ground walking) as done by Holgate et al. (2009) on the prosthetic ankle SPARKy.

15 minute talk format. I will present the design of a virtual constraint controller based on the COP and rollover shape, which drives the ankle and/or knee joints of a prosthetic leg. In the case of ankle-foot rocker shape, the kinematic constraint is equivalent to a one-to-one mapping from COP distance to ankle angle. This provides a desired ankle angle—a function of COP feedback—around which a control law can be defined. I have implemented a proportional-derivative controller (with respect to the tracking error) on a computational walking model and verified that stable gaits can be achieved for a range of desired rocker shapes. This control strategy is being tested on the Vanderbilt leg at the Center for Bionic Medicine, so these capstone experiments will be ready for presentation by the time of the 2012 *Dynamic Walking Conference*. My hope is that the robustness and simplicity of this time-invariant strategy will address a critical barrier that currently prevents the clinical acceptance and accessibility of powered prosthetic legs.

30 minute talk format. In the extended talk format I could also present recent experiments with able-bodied human subjects testing my hypothesis that human joint patterns depend on the COP as a phase variable rather than the traditional view of time. Subjects walked over a robotic force plate that randomly perturbed the stance ankle, violating the one-to-one relationship between COP and time during the stance cycle. We observed that the ankle angle converges back to the nominal trajectory in phase domain but not time domain, showing that human joint patterns are more accurately parameterized—and perhaps controlled—by the COP. This work will have significant implications on how researchers view human gait patterns (in time domain vs. phase domain) and the subsequent design of robot controllers.

Discussion Outline. I envision that this talk will motivate a spirited discussion in one of two directions, both of which are significant to the future of the dynamic walking field:

- Biomimetic approaches for autonomous and wearable robots are becoming more complex and difficult to analyze from a stability standpoint. Should we continue to sacrifice simplicity and rigor for biomimetic behavior, or can we strike a balance? I will propose that using neuromechanical principles in the context of theoretical control methods (e.g., virtual constraints) is one way to strike this critical balance.
- If the human nervous system uses a biomechanical sense of phase to control the progression of joint motion during walking, what implications would this have on the theory of Central Pattern Generation? What does this say about current control models based on time-dependent trajectories or discretized phases of the gait cycle?

Format. This presentation will feature many scientific results and experimental videos that have never been shown publicly and therefore an oral presentation of at least 15 minutes is preferred. The length of the talk will determine the scope of my presentation according to the two proposed options.

Keywords. Prosthetics, human walking, control

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