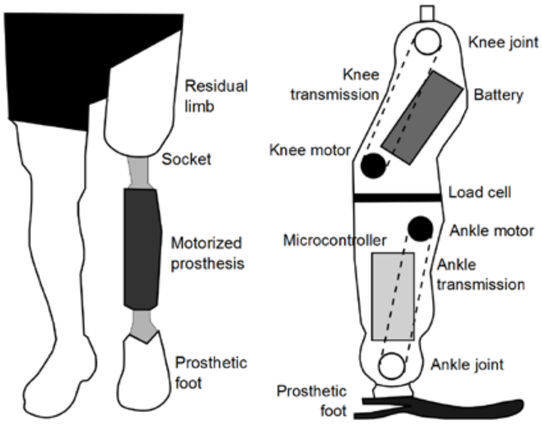
# Control of Powered Prosthetic Legs

Amputee locomotion is slower, less stable, and requires more metabolic energy than able-bodied locomotion. Lower-limb amputees fall more frequently than able-bodied individuals and often struggle to navigate inclines such as ramps, hills, and especially stairs. These challenges can be attributed largely to the use of *mechanically passive* prosthetic legs, which do not contribute positively to the energetics of gait, as do the muscles of the biological leg. Powered (or robotic) prosthetic legs could significantly improve mobility and quality of life for lower-limb amputees (including nearly one million Americans), but control challenges limit the performance and clinical feasibility of today's devices.

## State of the Art in Lower-Limb Prosthetic Control Systems

With the addition of sensors and motors, prosthetic legs must continuously make control decisions throughout the gait cycle, thus increasing the complexity of these devices. This complexity is currently handled by discretizing the gait cycle into multiple periods, each having its own separate control model. Each control model may enforce desired stiffness and viscosity characteristics or track predefined patterns of angles, velocities, or torques at the joints. To switch between control models at appropriate times, the prosthetic leg uses sensor measurements to estimate the phase—or location in the gait cycle.




*Drawing of above-knee amputee wearing a powered/motorized prosthetic leg (left), and enlarged schematic diagram of the experimental* Vanderbilt *prosthetic leg (right)*

## Limitations of the State of the Art

This approach to prosthetic leg control poses two key problems: (1) reliability of the phase estimate for switching control models, and (2) difficulty of tuning control parameters for several control models to each patient and task. An error in the phase estimate can cause the prosthesis to enact the wrong control model at the wrong time (e.g., swing period during stance), potentially causing the patient to fall. Even if the phase estimate is correct, each control model must be carefully tuned by a team of clinicians or researchers to work correctly for a particular patient performing a particular task. Some prosthetic control systems have five discrete periods of gait with more than a dozen control parameters per joint per period. Multiple tasks (e.g., walking, standing, stair climbing) add up to hundreds of parameters for a multi-joint prosthetic leg, presenting a critical challenge to the clinical viability of these high-tech devices.

## How Can Control Theory Contribute?

- Nonlinear filtering techniques for accurately estimating the phase of gait
- Optimization methods to *automatically* determine patient-specific control parameters for multiple periods of gait and different tasks
- Nonlinear control methods to unify the entire gait cycle under one control law
- Simultaneous stabilization theory to operate across multiple periods, tasks, and patients
- Formal verification methods to certify safe operating conditions

## Application to Orthotics/Exoskeletons

Control theory can also be applied to powered orthoses or exoskeletons that replicate lost leg function after spinal cord injury or assist locomotion after stroke. This application will present new challenges in designing control systems around human limbs, modeling limb mass/inertia, and compensating for muscle spasticity (i.e., abnormal resistance to muscle stretch due to a neurological impairment).

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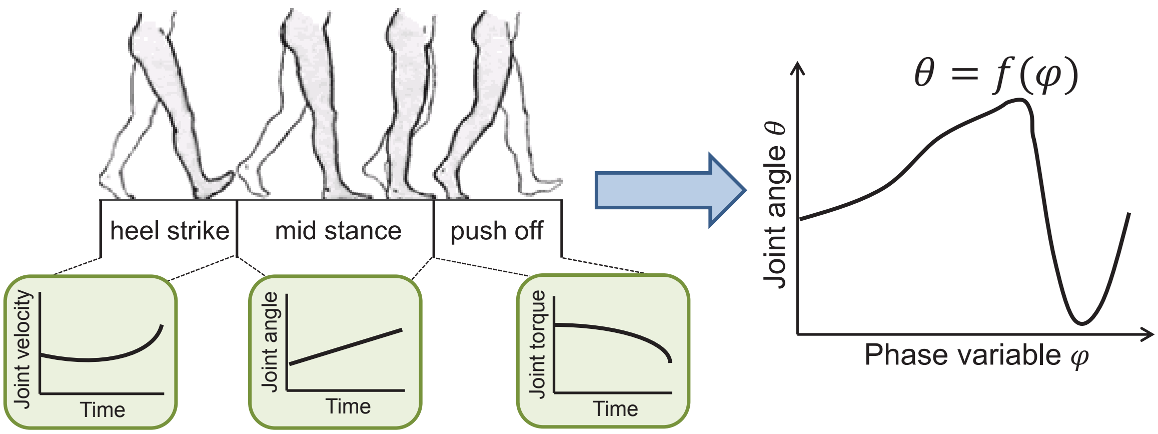
## From Walking Robots to Prosthetic Legs: Phase-Based Virtual Constraint Control

Some of these challenges could be addressed by parametrizing a nonlinear control model with a mechanical representation of the gait cycle phase, which could be continuously measured by a prosthesis to match the human body's progression through the cycle. Feedback controllers for autonomous walking robots have been developed that "virtually" enforce kinematic constraints, which define desired joint patterns as functions of a mechanical phase variable (e.g., hip position). These phase-based patterns, known as *virtual constraints*, have recently enabled bipedal robots to walk, run, and climb stairs, presenting an emerging opportunity to address a key roadblock in prosthetic technology.

## Recent Results

Researchers are currently investigating the use of biologically inspired virtual constraints to make prosthetic legs more robust and easily tuned than with controllers used to date. In particular, researchers at the Rehabilitation Institute of Chicago programmed the powered *Vanderbilt leg* to control its knee and ankle patterns based on the heel-to-toe movement of the center of pressure—the point on the foot sole where the cumulative reaction force is imparted against the ground. A recent study successfully tested this prosthetic control system on three above-knee amputee subjects.




*Conceptual diagram of shift from sequential control to virtual constraint control, where joint patterns are characterized by continuous functions of a mechanical phase variable*

## Remaining Challenges With Virtual Constraints

- Measuring a phase variable from the prosthesis during the swing period
- Modeling virtual constraints for different tasks such as stair climbing
- Feedback linearization to precisely enforce virtual constraints for high-performance tasks such as running
- Neural interfaces for subconsciously commanding the leg to perform different tasks
- Clinical trials with virtual constraints in a take-home prosthetic leg

*An above-knee amputee testing a virtual constraint controller on the Vanderbilt leg at the Rehabilitation Institute of Chicago*

*For more information: R.D. Gregg and J.W. Sensinger, Towards biomimetic virtual constraint control of a powered prosthetic leg, IEEE Transactions on Control Systems Technology, 2013; R.D. Gregg et al., Experimental effective shape control of a powered transfemoral prosthesis, IEEE International Conference on Rehabilitation Robotics, Seattle, WA, 2013.*