# Learning Bipedal Locomotion by Demonstration

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**The Problem:** To develop a bipedal locomotion control system, based on learning by demonstration, that achieves robust, realistic-looking gaits.

**Motivation:** A locomotion control system could be used in active orthotics; orthotic braces with actuators attached to augment the muscles of a patient. This would allow patients with a variety of neuro-muscular ailments to walk in an easier, more natural way than is currently possible with passive orthotics. A similar technology could be used for prosthetics to assist patients with amputations of one or both legs, below or above the knee. The control system could also be used to build bipedal robots with better, more human-like walking capabilities than has currently been achieved. Finally, computer animations could also benefit greatly from simulated human models that walk and run in a realistic way.

**Previous Work:** Many approaches have been used to control bipedal walking systems [1, 2, 3]. Collectively, these systems (simulated and real), have walked on slopes, over steps and small obstacles, and have achieved running. However, it is fair to say that the field is still a long way from robots that can walk as well as humans can. Given that biological evolution has provided a highly optimized locomotion mechanism, it makes sense to investigate whether a control system that learns from human walking demonstrations can achieve improved robotic locomotion.

In recent years, there has been a great deal of research in the area of learning by demonstration [4, 5, 6]. This activity has been fueled partly by the exponential increase in computing power, and by recent developments in the field of machine learning. Much of this research has focused on robot manipulator control. The recent advances in this field create a perfect opportunity to apply these new techniques to the more difficult problem of robot bipedal locomotion.

**Approach:** Walking motion trajectories used in this effort have been obtained from Spaulding Rehabilitation Hospital, in Boston. This data covers a variety of gaits and walking speeds for both normal and handicapped individuals.

Deriving automatic locomotion control systems from this data requires combination of a number of advanced technologies. These include a variety of learning algorithms, as well as advanced, high-performance dynamic simulations. The demanding requirements of this application will require innovation in both of these areas. For example, high-fidelity dynamics simulations of robotic systems are computationally intensive. Given that these serve as the basis for learning trials, there is significant benefit to be gained from speed improvements in these algorithms.

Once a better understanding of control laws has been achieved via the learning algorithms, it will be possible to estimate walking states based on a limited set of sensor inputs. Since the motion capture data includes trajectories from patients with walking handicaps, it will be possible to build observers that estimate the state of the patient and anticipate intent. This will allow for development of orthotic devices that augment the action of weakened muscles. The overall configuration of the control system is shown below.

**Difficulty:** Human-realistic, robust walking has not been achieved, not even in simulations that realistically model link dynamics and interaction with the ground. One reason for this is that it requires models that are generally more complex than the ones currently used; the morphology of the models needs to more closely mimic that of humans. This additional complexity greatly increases the complexity of the control problem. The state space becomes huge, and the possible control decisions are essentially infinite. For this reason, it is useful to seek guidance from an expert source: the motion trajectories for human walking. Given that these represent a near-optimal solution to the problem, these can be used to greatly reduce the search space of interest. In addition, movement primitives can be

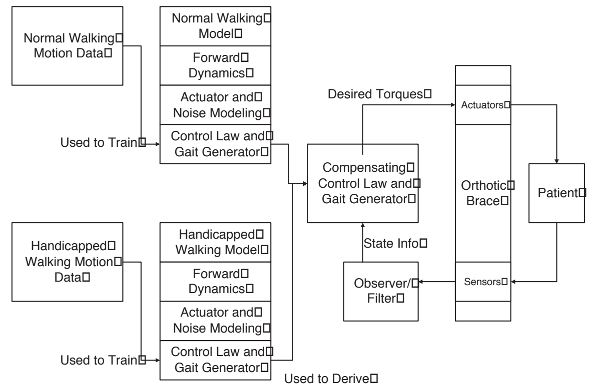


Figure 1: Orthotic Control System Configuration

extracted so that the control problem is transformed from one of searching the (huge) state space of the robot, to searching the much smaller space of combinations of movement primitives.

Estimation of walking state for the purpose of controlling an orthotic device is also a difficult problem. The minimal set of required sensor inputs is unknown, and is likely to vary depending on the type of handicap. Also, the control system will have to calibrate itself automatically to conform to the variations in size and behavior of the users.

**Impact:** Development of control models that result in human-like locomotion would be of great benefit to any robotic or bionic locomotion effort. The control models developed in this project could be adapted to a large variety of robots, allowing them to more closely approximate the capabilities of ordinary humans. The use of such models for orthotics and exoskeletons would allow people with handicaps to better navigate terrain the way non-handicapped people do. The use of such models in computer games would provide a more realistic experience for the user.

**Future Work:** The techniques developed as part of this project could be extended to analyze more complex dynamic motions such as the ones used in sports or dance. This would allow for improving the capabilities, not just of robots, but potentially, of humans as well. For example, if the control laws of a human expert at such an activity (a champion golfer or professional dance competitor for example) could be captured, they could be used to train less expert individuals and improve their performance. Such control models could also potentially be useful in exoskeletons that increase the capabilities of their users.

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**References:**

[1] A. Fod, M. Mataric, and O. C. Jenkins. Automated extraction of primitives for movement classification. *Humanoids 2000*, September 2000.

[2] J. Pratt, P. Dilworth, and G. Pratt. Virtual model control of a bipedal walking robot. *Proceedings of the 1997 International Conference on Robotics and Automation*, 1997.

[3] J. Pratt and G. Pratt. Intuitive control of a planar bipedal walking robot. *Proceedings of the 1998 International Conference on Robotics and Automation (ICRA '98)*, 1998.

[4] J. Pratt and G. Pratt. Exploiting natural dynamics in the control of a 3d bipedal walking simulation. *International Conference on Climbing and Walking Robots (CLAWAR99)*, September 1999.

[5] S. Schaal. Is imitation learning the route to humanoid robots? *Trends in Cognitive Sciences 3*, pages 233–242, 1999.

[6] J. Yamaguchi, A. Takanishi, and I. Kato. Development of a biped robot compensating for three-axis moment by trunk motion. *Proceedings of the IEEE/RSJ International Conference on Intelligent Robotics and Systems*, pages 561–566, 1993.