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Exploiting Natural Dynamics in the Control of a 3D Bipedal Walking Simulation

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Abstract

Natural dynamics can be exploited in the control of bipedal walking robots: the swing leg can swing freely once started; a kneecap can be used to prevent the leg from inverting; and a compliant ankle can be used to naturally transfer the center of pressure along the foot and help in toe off. Each of these mechanisms helps make control easier to achieve and results in motion that is smooth and natural looking.

We describe a simple control algorithm using these natural mechanisms which requires very little computation. The necessary sensing consists of joint angles and velocities, body pitch and angular velocity, and ground reaction forces. This algorithm is an extension to the algorithm we presented in [16] for a planar walker. To control lateral stability, we use lateral foot placement and ankle torque.

Using this simple algorithm, we have controlled a seven link, twelve degree of freedom, three dimensional bipedal robot simulation to walk. Video and more information can be found at http://www.ai.mit.edu/projects/leglab/

1 Introduction

Many researchers [1, 4, 5, 6, 11], starting with Mc Geer and his passive dynamic walker, have exploited natural dynamics in order to make walking machines which are fully passive. These devices rely completely on their dynamics, and interaction with gravity, in order to walk.

Passive walkers have limitations, of course, such as limited capabilities and the need to walk down a slope. Powered robots [7, 18, 17, 15, 3, 9, 10, 12, 21, 22] can avoid these limitations. However, the control of powered bipedal robots has often been very complicated and the resultant motion often looks unnatural and is inefficient. Many of the controllers for powered robots are model based, requiring an accurate model of

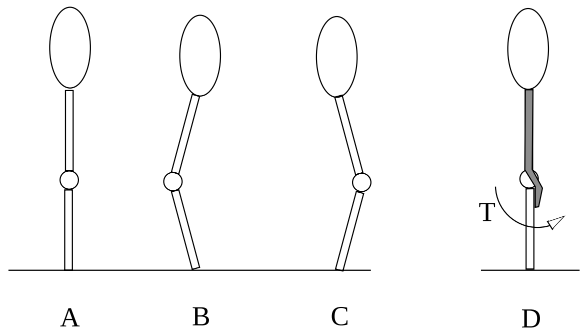

Figure 1: Diagram illustrating kneecap advantages. Without a kneecap, a biped with a straight support leg is in an unstable buckling configuration (A). Feedback control will result in chatter between knee inflections B and C due to delay, etc. With a kneecap (D), a constant torque with no feedback is enough to stablize the system against buckling.

the dynamics of the robot in order to work. Several of the robots use trajectory tracking approaches which require pre-specified trajectories of either the body or the joints themselves.

In this paper, we describe an approach to powered bipedal walking which exploits the natural dynamics of the robot and requires only a simple control algorithm. We exploit three different natural mechanisms. We use a knee cap to prevent the leg from inverting, which makes control of height easy. We use a compliant ankle limit so that the center of pressure on the foot travels forward with the center of mass of the body. And we exploit the natural swing dynamics of the leg to make swing control simpler and natural looking.

We present an algorithm, following this approach, for the control of a three dimensional bipedal walking simulation. The algorithm is a direct extension of the algorithm we presented in [16] for planar bipedal walkers. The algorithm stabilizes lateral motion through foot placement and ankle torque.

2 Natural Dynamic Mechanisms

2.1 Knee Cap

Walking with straight support legs is more efficient than with bent legs since energy requirements in muscles and motors are proportional to the torque at the joint, even if there is no velocity. However, since the leg must support the weight of the body, a straight leg poses an interesting challenge. Figure 1 illustrates the issue. When the body is directly over the foot (A), no torque is required at the knee. However, this is an unstable latch configuration. If the knee moves slightly either way, the leg will buckle (B or C). It is challenging to control this situation. Due to controller non-idealities (bandwidth limitation, delays, etc.) a straight knee controller will typically exhibit chatter between configurations B and C.

Adding a knee cap (D) can greatly simplify the control and make the resultant motion smoother and more efficient. A very simple control technique to keep the leg straight is to apply a constant torque so that the knee pushes against the stop. Of course other techniques can be used. Also, if the line of force on the body passes in front of the kneecap, the knee will be locked against the kneecap without any actuator torque.

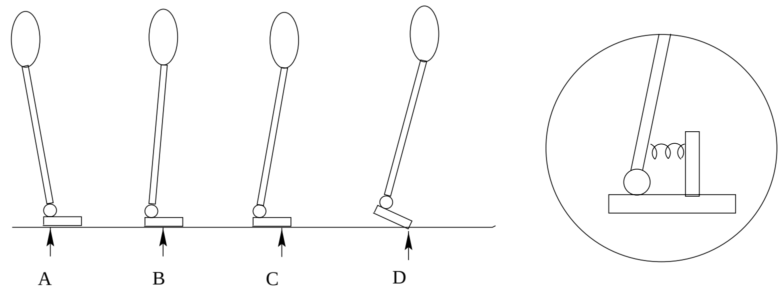

Figure 2: Diagram illustrating compliant ankle. In normal walking, the center of pressure on the foot travels forward as the center of mass travels forward (A-D). A compliant ankle (insert) can naturally achieve this effect. However, energy injection at toe off requires actuation.

2.2 Compliant Ankle

Feet and ankles provide many benefits to bipedal walking. They reduce velocity fluctuations since the center of pressure on the foot can travel forward, staying below the center of mass of the body. They also help to control speed and to inject energy at the end of the stride through toe off.

The torque at the ankle can be controlled actively. However, torque requirements can be quite high, since the foot provides a significant lever arm when the center of pressure is near the toe. A compliant ankle provides most of the benefits of a foot and ankle but without the torque requirements. An actuator can then be used in addition to the passive ankle for fine control and energy injection at toe off. Figure 2 illustrates the situation. In configuration A, the center of mass is behind the foot and there is zero ankle torque. In configurations B and C, the center of mass is travelling forward. The ankle torque increases, thereby moving the center of pressure of the foot forward from the heel to the toe. In configuration D, the robot goes into toe off, releasing the energy stored in configurations B and C and perhaps injecting some more, through active torques, to maintain walking. The inset shows a simple spring configuration which can give the ankle the desired compliance.

Choosing an adequate spring torque versus displacement curve is important in achieving the desired behavior. In the simulation discussed below we use a quadratic spring ($\tau = k(\theta - \theta_0)^2$) and tune the stiffness parameter. For the robot we use a rubber stop and adjust the position of the stop for best results.

2.3 Passive Swing Leg

Most powered bipedal walkers used control techniques similar to those used for robotic arms to control the swing leg along a trajectory to a desired landing position. However, with a suitable leg, the natural swing dynamics are such that once the swing starts, the leg will continue without any intervention, as illustrated in Figure 3. Gravity alone can be used to initiate swing, as in the case of the passive dynamic walkers. Hip torque can be added in order to make the leg swing faster as in animals.

We use the passive swing properties of the leg in the control of our simulation. The hip is servoed forward to a desired angle and the knee is allowed to swing freely. At the end of the swing, moderate damping is added to the knee to prevent it from banging into the knee cap and finally it is locked once it hits the knee cap.

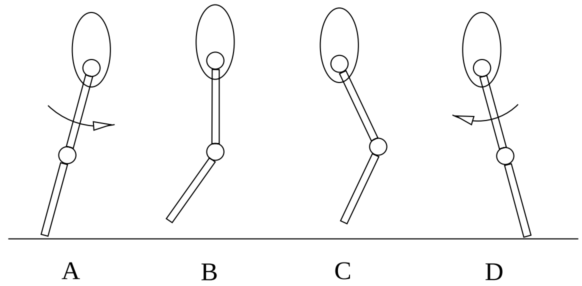

Figure 3: Diagram illustrating passive swing. Swing is initiated (A) through a forward torque on the hip, supplied either by hip actuators or gravity. The leg can swing passively (B - C) until swing is stopped (D) through a backward torque on the hip, again supplied either by hip actuators or gravity.

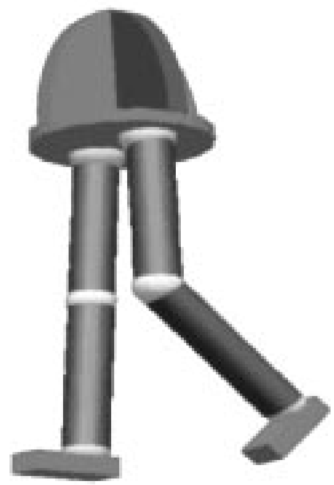

Figure 4: Three Dimensional bipedal walking simulation. The robot has twelve degrees of freedom: three in each hip, one in each knee, and two in each ankle.

In the next section, we describe an algorithm which exploits the three natural mechanisms, described above, in the control of a simulated bipedal robot.

3 Simulation Algorithm

We use the natural dynamic mechanisms described above in the control of a simulated seven link, twelve degree of freedom, bipedal robot. The simulation has an actuated hip, knee, and ankle on each leg.

The simulation algorithm is summarized in Figure 5. Each leg acts separately and has a simple state machine. The leg can be in either Support, Toe Off, Swing, or Straighten states. In Support and Toe Off states, the hip is used to servo body pitch to maintain balance and the knee is locked to maintain height. In Support state, the ankle pitch is unactuated - only the passive ankle compliance is present. The ankle roll is used to dampen lateral velocity. During Toe Off state, the ankle is servoed to an angle using a Proportional-Derivative (PD) controller in addition to its passive compliance. The transition from Support to Toe Off occurs when the heel lifts off the ground due to the passive compliance of the ankle.

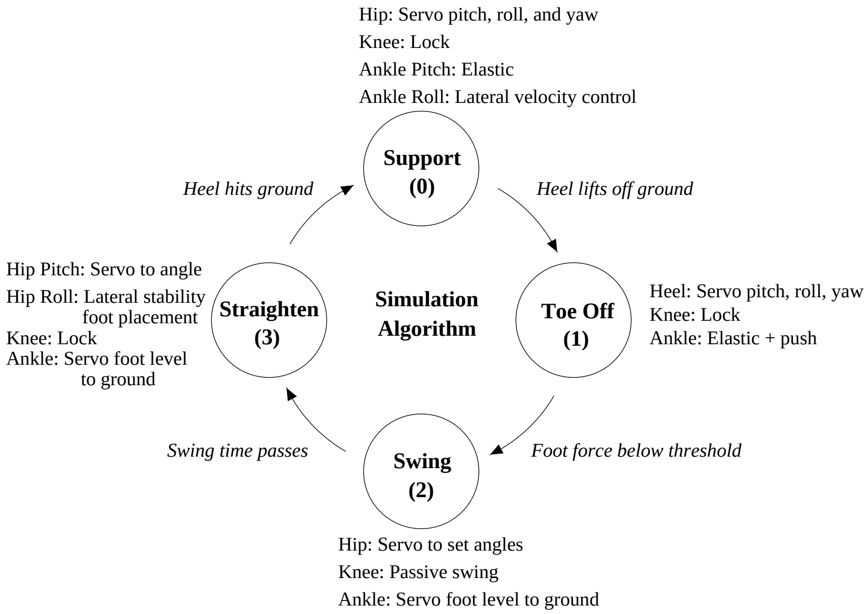

Figure 5: Simulation Algorithm. Each leg has a state machine which is in one of four states. State transition conditions and actions in each state are shown.

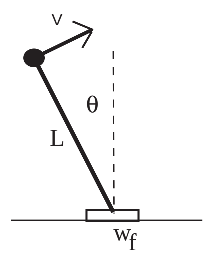

Figure 6: Simple pendulum model illustrating the effects of foot placement and ankle torque on eliminating lateral velocity and hence providing for lateral stability.

The robot transitions from Toe Off to Swing when the force on the foot falls below a certain threshold. In both Swing and Straighten states the hip pitch is servoed to an angle using a PD controller and the foot is servoed to be level with the ground so that the robot does not stub its toe. In Straighten state, the hip roll is used for lateral foot placement, to control lateral velocity. In Swing state, the knee is damped while in Straighten state the knee is locked straight using a PD controller.

The robot transitions from Swing to Straighten state after a constant amount of time passes. Finally, the robot transitions from Straighten to Support state when the heel of the swing leg hits the ground.

3.1 Lateral Stability

To control lateral stability in the frontal plane, we use foot placement and ankle torque. Figure 6 shows a simple pendulum model for determining foot placement. The initial kinetic energy is

$$E_k = \frac{1}{2}mv^2 \tag{1}$$

The change in potential energy is

$$\Delta E_p = mgl(1 - \cos\theta) \tag{2}$$

Setting the change in potential energy equal to the kinetic energy we get

$$\cos\theta = 1 - \frac{v^2}{2gl} \tag{3}$$

For small angle approximation, we get

$$\theta = \frac{v}{\sqrt{gl}} \tag{4}$$

We use equation 4 for determining lateral foot placement. There may be some error in the foot placement. To overcome this error, we use ankle torque, after the foot is placed.

The ankle torque is limited due to the small width of the feet. A static analysis gives us,

$$\tau_{max} = mgw_f \tag{5}$$

where w_f is half the width of the foot.

The energy that can be absorbed by the ankle is thus,

$$\Delta E = mgw_f\theta \tag{6}$$

Combining this with the potential energy and solving for θ, we get

$$\theta = \frac{\pm 2gw_f + \sqrt{(2gw_f)^2 + 4glv^2}}{2gl} \tag{7}$$

This equation is plotted in Figure 7. The parameter values we use are $w_f = 0.5m$, $l = 1.0m$, $g = 10.0\frac{m}{s^2}$. We see that ankle torque can compensate for errors in lateral foot placement, even with a narrow foot.

3.2 Simulation Results

The simulation parameters were first manually tuned, and then fine tuned using a genetic algorithm with efficiency as its cost function. Efficiency was computed as distance travelled divided by total joint energy after ten seconds of walking. Total joint energy was computed by integrating the total joint power which is the sum of the absolute values of the mechanical power at each joint:

$$E_{tot} = \int P_{tot}\, dt, \quad P_{tot} = \sum_{joints} |P_{joint}|, \quad P_{joint} = \tau_{joint}\, \dot{\theta}_{joint} \tag{8}$$

After a couple generations, naturally looking walking resulted. A time elapsed animation is shown in Figure 8. The drawings on the left show the swing phase of one leg. The drawings on the right show several steps. The right leg is dotted while the left leg is solid. Lines show the path of the tips of the feet and the hip trajectory. Results are plotted graphically in Figure 9.

We see that the simulated robot walked at a moderate speed (approximately 0.8 m/s) and had a natural looking gait. It is interesting that the algorithm does not contain any explicit speed control mechanism, yet speed is stabilized. We speculate that this is due

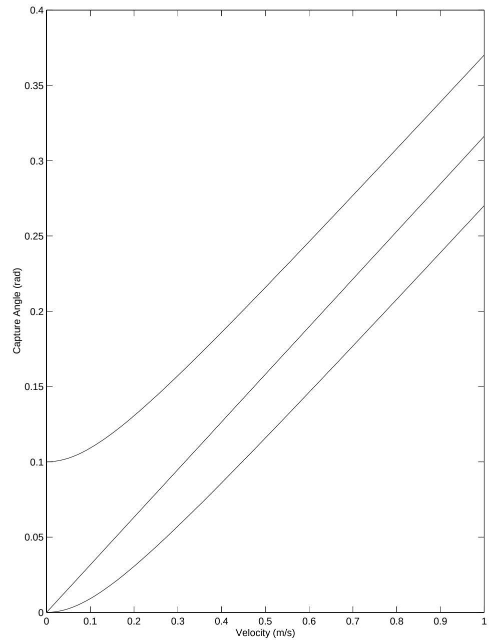

Figure 7: Range of Capture Angle vs. lateral velocity for a simple pendulum model with ankle torque. The range of angles show that ankle torque can be used to correct for errors in lateral foot placement.

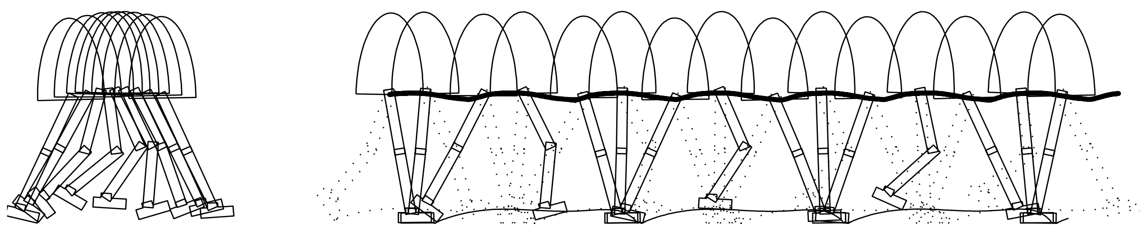

Figure 8: Elapsed time snapshot of the simulated robot walking data. The right leg is dotted while the left leg is solid. Lines show the path of the tips of the feet and the hip trajectory. The robot walks from left to right.

to the natural system dynamics, in the same way that speed is naturally stabilized in the passive dynamic walkers.

4 Conclusions and Future Work

Three dimensional bipedal walking can be achieved by a simple control algorithm which exploits the natural dynamics of a kneecap, compliant ankle, and passive swing leg. Lateral foot placement and ankle torque can be used for lateral stability. The resultant motion is fairly smooth and efficient. This work may help bridge the gap between passive dynamic walkers and powered bipedal robots.

The simulation settles on a stable speed of walking of approximately 0.8 m/s. However, nowhere in the controller is speed explicitly controlled. We believe that the speed is stabilized in a similar way to passive dynamic walking machines. That is, if the robot goes too fast, it naturally takes a longer step due to the natural swing leg dynamics and hence slows down on the next step. Similarly, if the robot moves too slowly, it naturally

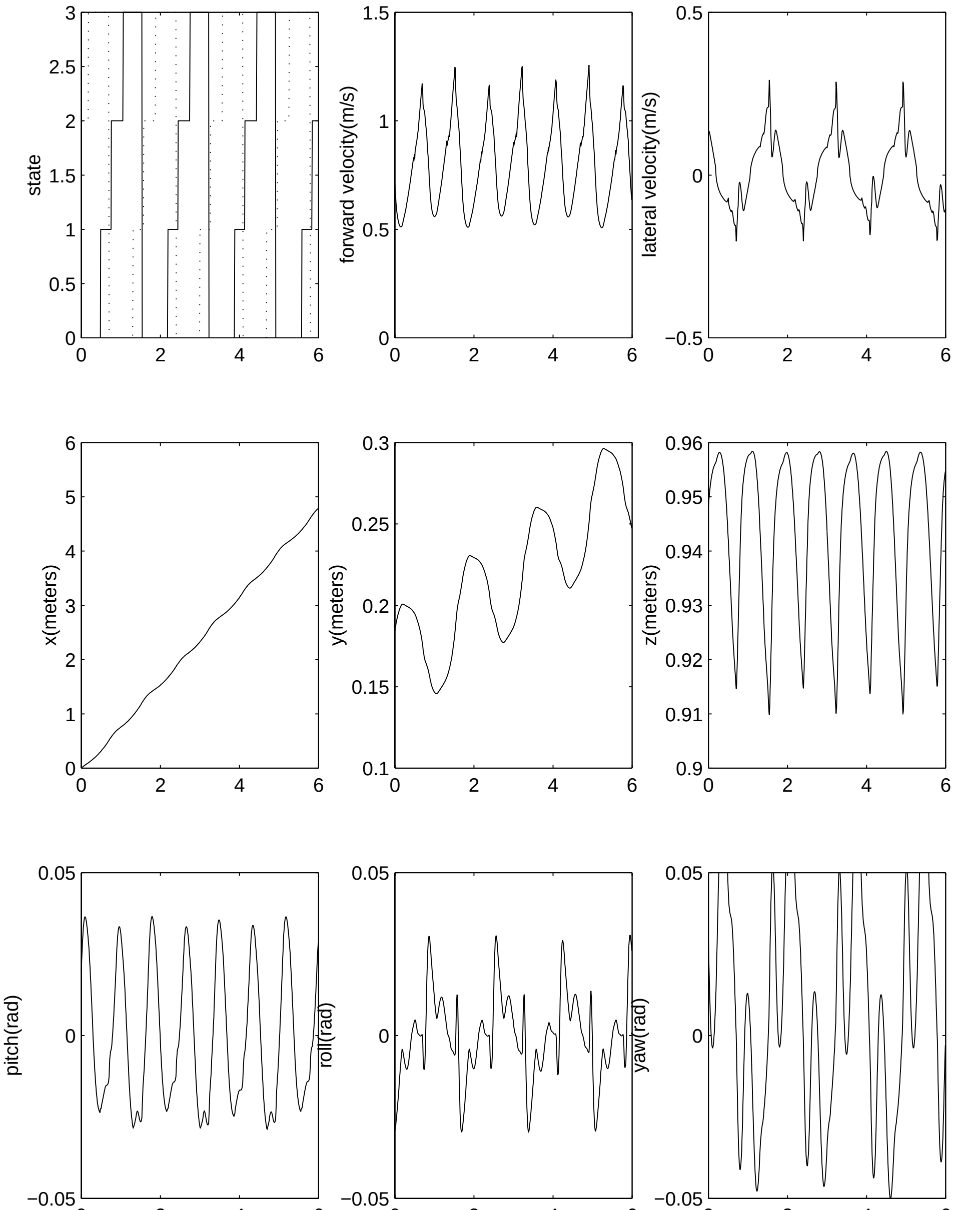

Figure 9: Simulation data. The first row contains, left to right, state of the legs, forward velocity, and lateral velocity. The second row contains forward distance, lateral motion, and body height. The last row contains body pitch, roll, and yaw.

takes a shorter step and hence speeds up on the next step.

In order to exploit the natural dynamics of a walking robot, it is important that the inertia and friction of the actuators does not dominate the dynamics of the legs. In our robots we use Series Elastic Actuators which result in very little unwanted dynamics. These actuators have good force dynamic range and low force offset which are important in natural and efficient walking. We are continuing to use these actuators in the design of several new walking robots.

References

[1] J. Adolfsson, H. Dankowicz, and A. Nordmark. 3-d stable gait in passive bipedal mechanisms. *Proceedings of 357 Euromech*, 1998.

[2] R. Q. Van der Linde. Active leg compliance for passive walking. *IEEE Conference on Robotics and Automation*, pages 2339–2345, 1998.

[3] E. Dunn and R. Howe. Foot placement and velocity control in smooth bipedal walking. *IEEE Conference on Robotics and Automation*, pages 578–583, 1996.

[4] J. Fowble and A. Kuo. Stability and control of passive locomotion in 3d. *Proceedings of the Conference on Biomechanics and Neural Control of Movement*, pages 28–29, 1996.

[5] M. Garcia, A. Chatterjee, and A. Ruina. Speed, efficiency, and stability of small-slope 2d passive dynamic bipedal walking. *IEEE International Conference on Robotics and Automation*, pages 2351–2356, 1998.

[6] A. Goswami, B. Espiau, and A. Keramane. Limit cycles in a passive compass gait biped and passivity-mimicking control laws. *Journal of Autonomous Robots*, 1997.

[7] K. Hirai, M. Hirose, Y. Haikawa, and T. Takenaka. The development of honda humanoid robot. *IEEE Conference on Robotics and Automation*, 1998.

[8] L. Jalics, H. Hemami, and B. Clymer. A control strategy for adaptive bipedal locomotion. *IEEE Conference on Robotics and Automation*, pages 563–569, 1996.

[9] S. Kajita and K.Tani. Adaptive gait control of a biped robot based on realtime sensing of the ground profile. *IEEE Conference on Robotics and Automation*, pages 570–577, 1996.

[10] A. Kun and W. T. Miller. Adaptive dynamic balance of a biped robot using neural networks. *IEEE Conference on Robotics and Automation*, pages 240–245, 1996.

[11] Tad McGeer. Passive dynamic walking. *International Journal of Robotics Research*, 9(2):62–82, 1990.

[12] H. Miura and I. Shimoyama. Dynamic walk of a biped. *International Journal of Robotics Research*, 3(2):60–74, 1984.

[13] Simon Mochon and Thomas A. McMahon. Ballistic walking: An improved model. *Mathematical Biosciences*, 52:241–260, 1979.

[14] Gill A. Pratt and Matthew M. Williamson. Series elastic actuators. *IEEE International Conference on Intelligent Robots and Systems*, 1:399–406, 1995.

[15] J. Pratt, P. Dilworth, and G. Pratt. Virtual model control of a bipedal walking robot. *IEEE Conference on Robotics and Automation*, pages 193–198, 1997.

[16] J. Pratt and G. Pratt. Exploiting natural dynamics in the control of a planar bipedal walking robot. *Proceedings of the Thirty-Sixth Annual Allerton Conference on Communication, Control, and Computing*, pages 739–748, 1998.

[17] J. Pratt and G. Pratt. Intuitive control of a planar bipedal walking robot. *IEEE Conference on Robotics and Automation*, 1998.

[18] Marc H. Raibert. *Legged Robots That Balance*. MIT Press, Cambridge, MA, 1986.

[19] M. Vukobratovic, B. Borovac, D. Surla, and D. Stokic. *Biped Locomotion: Dynamics, Stability, Control, and Applications*. Springer-Verlag, Berlin, 1990.

[20] Matthew M. Williamson. Exploiting natural dynamics in robot control. *Proceedings of the Fourth European Meeting on Cybernetics and Systems Research (EMCSR '98)*, 1998.

[21] J. Yamaguchi, A. Takanishi, and I. Kato. Development of a biped walking robot adapting to a horizontally uneven surface. *IEEE International Conference on Intelligent Robots and Systems*, pages 1156–1163, 1994.

[22] K. Yi and Y. Zheng. Biped locomotion by reduced ankle power. *IEEE Conference on Robotics and Automation*, pages 584–589, 1996.