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# Powered bipedal robots based on unpowered walking toys

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**Unpowered bipedal devices which walk down gentle slopes have been in development, initially as toys, for more than one hundred years. Here we describe three powered robots based on these ramp-walking toys. Humanoid walking robots usually rely heavily on complicated feedback control strategies, have a limited learning ability, have gaits that look somewhat artificial, and use relatively more energy to walk than humans. In contrast, our robots have highly simplified control strategies. One of these is quick to learn a variety of motions. One can walk on somewhat uneven terrain. And one uses an order of magnitude less energy than previous powered bipedal robots. The natural and efficient motions of these minimally-controlled artificial animals support the idea of a similar coupling between structure and motion in real animals.**

Efficient and robust bipedal walking robots might some day be useful as relatively dispensable proxies for human fire fighters, nuclear reactor cleaners, soldiers or servants. In the mean time attempts to develop humanoid walking robots help to develop concepts for advanced prosthetics, serve as test systems for investigating control strategies for more general complex machines, provide designs for toys and approaches to automatic animation, and help test concepts about how humans (and more generally, animals) get around.

The remarkably engineered Honda Humanoid machines represent the state of the art. The 52 kg (510 N) Asimo [1] can not only walk straight on level ground but can start and stop, turn, step sideways, go up and down stairs, look around and avoid obstacles, shake hands and talk. This machine has broad flat feet so it can stand still, even on one foot. An on-board computer constantly monitors and controls all joint angles (ankle, knee, hip, etc) using highly-gear-reduced motors. The controlled joint-angles vary smoothly in time in a manner that trades mimicry of a walking person for a cautious gait designed to maintain balance. Asimo has a 10 amp-hour capacity 38.4V battery pack. It is said to be capable of walking at 1.6 km/hr for half an hour.

A key issue in locomotion is energy use. The energy effectiveness of level locomotion is most commonly measured by the dimensionless specific energetic cost of transport $c_{et}$ = (energy used)/(weight)(distance traveled) (e.g.,[2]). A related measure is mechanical energy effectiveness $c_{mt}$ which assigns an energy cost only to the mechanical work of the actuators and not the chemical or electrical energy used. Measuring effectiveness by $c_{mt}$ isolates the effectiveness of the mechanical design and control-system aspects from the motor/muscle efficiency. As a rough guide $c_{mt} \approx c_{et}/4$ for both machines powered by combustion and animals because both muscles and gas motors are typically about 25% efficient. For reference, the 800 pound, 12 horsepower, 30 mile per hour Wright Flyer had $c_{mt} \approx 0.18$, an automobile driving at a constant speed can have mechanical energy effectiveness as low as about $c_{mt} \approx 0.015$, a relaxed bicyclist has $c_{mt} \approx 0.01$, a freight train has $c_{mt} \approx 0.003$, and a freighter has $c_{mt} \approx 0.001$. One can think of $c_{mt}$ as an effective coefficient of friction $\mu$. (Note that thermodynamic efficiency can not be used as an overall performance measure for level transport because the gravity force is orthogonal to the motion, so the energetic utility is zero.)

For Asimo, using the weight, battery capacity and speed information above, $c_{et} = 3.2$. For comfortably-paced human walking $c_{et} \approx 0.2$, as measured by "VO2" ("VO2" is an approximate acronym for the Volume of Oxygen consumed per unit time. It yields a respiration measure of the food energy used for a given activity [3, 4]). For walking humans $c_{mt} \approx c_{et}/4 \approx 0.2/4 = 0.05$. Although electrical motors can be 90% efficient or more, we might guess that Asimo's high-reduction gear trains are marginally back-driveable and thus have a conversion efficiency (mechanical work/electrical power) on the order of 50%. So we estimate that Asimo has a mechanical specific cost of transport on the order of $\approx c_{mt} \lesssim 3.2/2 \approx 1.6$. Thus, as measured either by energy used or by the work done by the motors and muscles, Asimo uses on the order of 20 times as much energy as a person (per unit weight per unit distance moved). Because the control of Asimo is based on maximizing stability and smoothness of motion and not energetic effectiveness, most of the energy might be used up by the motors alternately doing and absorbing work. Human evolution, on the other hand, has presumably selected against excessive energy use in locomotion.

There is an analogy between robot development and the development of early flying machines. In the late 1980s aeronautical engineer Tad McGeer proposed that powered walking robots might be better developed by paralleling the Wrights' development of powered flight [5], starting with development of energy-effective and stable machines powered only by gravity. The Wright brothers' major effort was to master the mechanics of unpowered flight. The Wrights achieved energy effectiveness through their wing designs, and stability using new control ideas. The Wrights drew inspiration from many sources including flying toys[6] and the coupling between leaning and steering in bicycles. The Wrights systematically developed a controllable glider with a small descent slope. Once they had done this they confidently substituted gasoline for gravity as a power source. On December 17, 1903, the first day they tried the idea, they succeeded at powered flight.

The robotic analog of a non-motorized plane flying down a glide slope is a non-motorized walking machine walking down a sloped surface. Ramp-walking toys go back at least to 1888 [11]. Ramp-walkers are also called passive-dynamic robots because the joint angles are unregulated; motions are passively determined by Newtonian dynamics. A ramp walker is just a collection of rigid objects connected by free hinges that is placed on a ramp. The parts are designed so that passive dynamics naturally produce walking motions. As opposed to Asimo which has every angle controlled at all times, in a passive-walker no angle is actively controlled at any time.

All known ramp-walking bipedal toys have inflexible legs and curved feet, as seen on the 1938 "Wilson Walkie" in Fig. 1a1. The feet on these toys are only gently-curved (with radius of front-to-back curvature greater than the height of the center of mass) and so can stand stably upright with parallel legs. When placed on a slightly-sloped ramp and given a small push, they walk downhill with the "very comical, awkward, waddling gait of the penguin" [7].

Ramp-walking toys became a topic of research with the Wright-inspired developments of McGeer. McGeer's capstone robot [5] is an advancement over the previous toys in that, in side view, it has motions that, rather than penguin-like, are

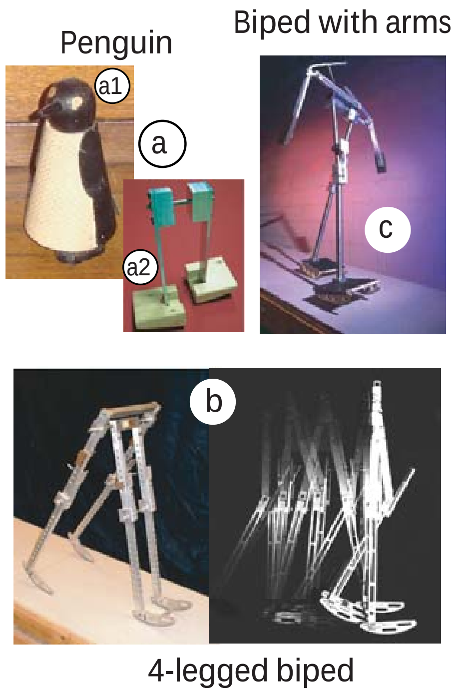


Figure 1: Ramp-walking (downhill, unpowered or passive-dynamic) robots are used as the source design. (a) is the Wilson "Walkie" [7] and our simplified slightly-improved version [8]. (b) is a copy [9] of McGeer's 4 legged biped design [5] (photo by Rudra Pratap), (c) is the passive biped with arms [10] (photo by Hank Morgan).

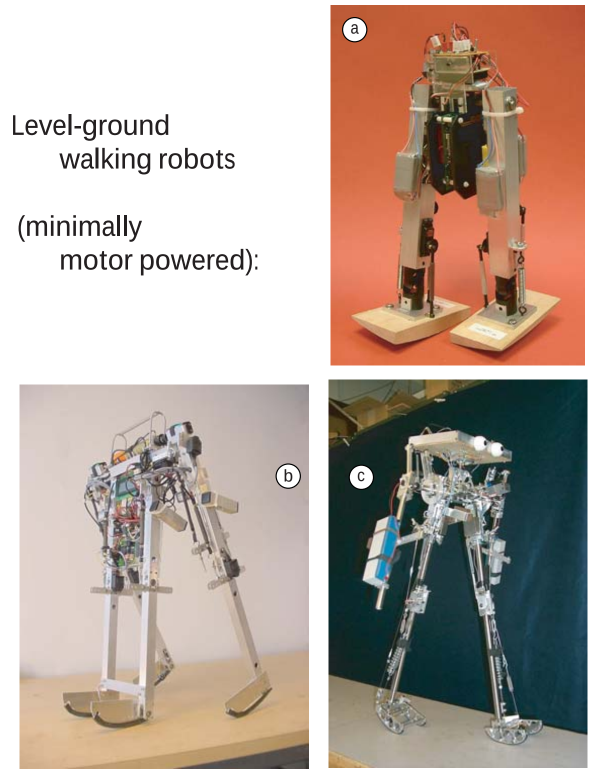


Figure 2: The powered and controlled robots here are based on the ramp-walking designs of Fig. 1. All make relatively low information-flow and energy demands of their controllers, sensors and actuators. (a) is MIT's simply-powered penguin design, (b) is Delft's hip-actuated 4 leg 'biped', (c) is Cornell's toe-off actuated biped with arms. These powered robots have motions close to their ramp-walking parents as can be seen on videos at http://www.tam.cornell.edu/~ruina/hplab/naturewalk.html.

startlingly human-like (Fig. 1b). To prevent falling sideways McGeer's 4-leg 'biped' has two pairs of legs, a synchronously-moving inner pair and a synchronously-moving outer pair. Each leg has a joint at the knee. The feet have smaller front-to-back curvature so his machines can not stand stably upright but only with legs splayed (Fig. 1b, left photo). McGeer's designs, as well as those that followed, are guided by numerical simulations making use of nonlinear dynamical systems theory (e.g., stability of limit cycles) of a type first proposed for gait analysis by Hurmuzlu [12].

In the same way that the Wrights learned about powered flight by learning what could be done without a motor, passive-dynamic robot research aims to learn the roles of nerves and muscles in animals, and computers and motors in robots, by learning what can be done without them. Using dynamic modeling and simulation unavailable in 1938, we have improved the grace and stability of the Wilson Walkie with a slightly different passive design (Fig. 1a2) having ellipsoidal rather than spherical feet [8]. Another design similar to the Wilson Walkie, 'the Tinkertoy' [13], has smaller-radius (front-to-back) and narrow feet and so can not stand stably upright or even with splayed legs. The Tinkertoy only balances when in motion, demonstrating that these ramp-walkers' motions are more than slight perturbations of standing-still. Fig. 1c shows the most anthropomorphic ramp-walker to date [10]; it is a true biped (two rather than four legs) and has knees and arms; it cannot stand with parallel legs but has wide feet so can stand with splayed legs. Its uncontrolled motions are sufficiently human-like to further hint that passive-dynamics are relevant to human architecture and motion.

Because air friction is small and friction of bearings at joints is also small, the ramp-walkers' gravitational potential energy is mostly spent at the collisions of the feet with the ground. (In machines with knees and a hyper-extension-limit, a small amount of energy is lost when the shank hits this limit.) Consequently, the passive-dynamic ramp-walkers can travel on arbitrarily small slopes in theory, and slopes between about 0.03 and 0.2 radians ($2° - 10°$) in practice [9]. For ramp-walkers and gliders $c_{mt}$ is the slope of descent.

With this knowledge about the energy effectiveness and stability of ramp-walking designs, somewhat analogous to the Wrights' knowledge about gliders, we were confident that we could make stable level-ground walking robots by simply adding a small amount of power and control. We have built three different powered robots in this way. Each walks stably on flat surfaces by using electric or pneumatic motors to restore the mechanical energy lost in collisions (Fig. 2). These robots, developed at three different laboratories, represent the first robots fully based on the idea of adding simple control and power to previously functioning ramp-walking robots.

The first of these (Fig. 2a), developed at MIT, is based on the toys in Fig. 1a. The passive design was modified by the addition of two actuated degrees of freedom (pitch and roll) which were added at the ankle. The hip joint was left passive. The second (Fig. 2b), developed at Delft, is a powered version of McGeer's four-legged biped. It uses pneumatic McKibben artificial muscles to actuate the hip and knees. Finally, a robot developed at Cornell (Fig. 2c) is based on the passive biped with arms and uses a motor to power ankle extension. Construction details for these machines are in the methods section and videos are at the web site in the caption of Fig. 2.

In contrast with standard approaches to robotics involving complicated dynamic models of the robot and high bandwidth real-time feedback control, these three robots all have simple control. Our hypothesis was that robots which are capable of stable walking down a ramp without any control should be easy to control when powered on a flat surface.

The MIT powered walker (Fig. 2a) was designed specifically to test this idea. In contrast to the massive design efforts put into the control system for Asimo, the control system for this robot was acquired automatically using a reinforcement learning algorithm[14, 15]. The penguin design was selected because it has only a small number of joints and actuators, which minimizes the combinatorial explosion of control strategies for the learning algorithm to select from. This design is also very stable; most failed attempts at walking end with the robot standing still instead of crashing to the ground. Due to this relative simplicity and the carefully designed passive properties of the robot, the MIT walker was able to quickly acquire a controller for robust walking, training in as little as 10-20 minutes. This training did not require any dynamic models nor baseline controllers, and was implemented completely online. The machine can start, stop, steer, and walk, with that penguin wobble, forwards and backwards at a range of small speeds.

Controllers for the Delft and Cornell walkers are even more simple and were designed by hand. Because these machines are based on open-loop control-free yet stable designs they need little feedback. For both of these robots the total information flow from sensors to the controlling circuits is on the order of 10 bits per step (one to three real numbers each step with 1%-10%, or 3-7 bit, accuracy for each number).

Most humanoids are confined to predictable laboratory floors. The Delft robot was designed to be stable in a more unpredictable environment. The artificial hip muscles not only power the robot but improve stability by quickly placing the swing leg in front of the body before the body falls forward [16, 17]. The Delft machine has a gait similar to that of its passive parent, McGeer's 4-leg biped design, but it is more stable; it can reliably walk on mildly rolling terrain. Walking at 0.4 m/s with 0.24 m steps the 7 Kg Delft robot consumes 36 Watts of electrical and compressed-gas energy (measured at the 4 atm regulated pressure, not at the largely-dissipated 58 atm cannister pressure) yielding $c_{et} \approx 1.3$. Measuring the torques at the joints as a function of angle and time we estimate the actual positive joint mechanical power as about 3 Watts leading to $c_{mt} \approx 0.1$. When ramp walking, this machine required a slope of about 0.06 radians ($c_{mt} \approx 0.06$) so this particular actuation is more costly than gravity.

We wanted to show that the natural-looking gait of the Cornell passive-biped-with-arms would be maintained if gravity power was replaced by injection of a small amount of motor power. A key control-design principle was to achieve energy effectiveness by never absorbing energy with the actuators. Thus the overall energy budget is, neglecting air and joint friction, a balance of positive actuator work and collisional loss. Power was injected by extending one ankle when the other foot makes ground contact. The 12.7 kg machine, walking at 0.44 m/s with 0.36 m steps, consumes a total of 11 Watts of battery power for the CPU, sensors, solenoids and motors. Measuring the ankle torques as a function of angle yields an average rate of positive mechanical work of about 3 watts. Thus this machine has energy effectiveness similar to that of a human with $c_{et} \approx 0.2$ and $c_{mt} \approx 0.06$. The similarity of the Delft and Cornell $c_{mt}$ values is not coincidental, they are based on similar passive designs. The Cornell robot has a relaxed gait that is more human-like to many eyes than that of any other robot to date.

The problem of artificially generating a naturally-flowing bipedal walk is less well defined and certainly more pedestrian than achieving take-off with a heavier-than-air flying machine. Nonetheless, the steps described here are somewhat analogous to the first powered Wright flight.

Since 1903 gliders have improved with glide-slopes now one fifth that of the Wright gliders, and powered flights going thousands of times higher and farther. We expect robot design to similarly improve in coming years. One would like a single robot to combine the adaptive control strategy of the MIT walker with the robustness of the Delft walker and the natural gait of the Cornell walker. This might come to pass through further control of passive-based robots like those presented here, or through attention to energy-efficiency in fully controlled robots like Asimo.

Whatever the future of humanoid robots, the success of human mimicry demonstrated here, without using trajectory control, strongly suggests an intimate relationship between body architecture and control in human walking.

## Methods

**MIT Penguin.** First we duplicated the Wilson design using two rigid bodies connected by a simple hinge. The gait was iteratively improved in simulation by changing the foot shape for a given leg length, hip width, and mass distribution. The resulting ramp-walker (figure 1a) walks smoothly down a variety of slopes. The powered version (figure 2a) uses tilt sensors, rate gyros, and potentiometers at each joint to sense the configuration of the robot, and servo motors to actuate the ankles. The completed robot weighs 2.75 kg, is 43cm tall, and has 6 internal degrees of freedom (each leg has one at the hip and two at the ankle). Before adding power or control we verified that this robot could walk stably downhill with the ankle joints locked.

The robot's control code runs at 200Hz on an embedded PC-104 computer running Linux. The robot runs autonomously; the computer and motors are powered by lithium-polymer battery packs, and communication is provided by wireless ethernet (802.11b). The learning controller, represented using a linear combination of local nonlinear basis functions, takes the absolute body angle and angular velocity of the robot as inputs and generates target angles for the ankle servo motors as outputs. The learning cost function quadratically penalizes deviation from the desired state on the return map of the system, taken around the point where the robot transfers support from the left foot to the right foot. Before learning, outputs were zero everywhere regardless of the inputs, and the robot was able to walk stably down a ramp. Lacking actuation it would then run out of energy when walking on the flat. Through a form of policy-gradient reinforcement learning [18], the feedback controller was trained to stabilize the walking gait on flat terrain. All learning trials were carried out on the physical biped with no offline simulations. The learned controller is quantifiably (using the eigenvalues of the return map) more stable than any controller we were able to design by hand, and recovers from most perturbations in as little as one step. The robot continually learns and adapts to the terrain as it walks.

**Delft 4-legged biped.** The powered robot weighs 7 kg with 3 internal degrees of freedom (one hip, two knees), and is 0.6 m tall. It is entirely autonomous with no energy or information flow from the outside.

The robot consists of two pairs of legs, one inner and one outer, which are attached at a hip joint. Each pair moves together (and is treated as a single leg) to constrain motion to the sagittal plane. Each leg has a mechanical stop at the knee to avoid hyper-extension, and a rigid ankle with an arc foot. Two counter-acting pairs of air-actuated tension-only McKibben artificial muscles provide a torque across the hip joint to power the walking motion. Across each knee joint, one artificial muscle (counteracted by a passive spring) is placed to lock it in place at knee strike and through stance. The muscles are fed with $CO_2$ from a 58 atm cannister, pressure-reduced in two steps to 4 atm through locally developed miniature pneumatics. Low-power two-state valves from SMC Pneumatics® connect the muscles either to the 4 atm supply pressure or to 0 atm.

McKibben muscles have a low stiffness when unactuated, leaving the joints behaving almost passively at zero pressure. At higher pressures the McKibben muscles behave as progressively stiffer springs. By activating opposing muscles in different proportions the relaxed angle of a joint can be controlled. This is applied at the hip where the artificial-muscles alternate in action. At the start of each step (determined by a foot switch) one muscle is set to 4 atm and the other to 0 atm, such that the swing leg is accelerated forward until the relaxed angle of the hip is reached, where it (approximately) stays due to damping in the muscles and in the joint.

A Universal Processor Board from Multi Motions® (based on the Microchip® PIC16F877 micro-controller) uses foot contact-switch signals to open or close the pneumatic valves. The control program is a state machine with two states: either the inner or the outer legs are in swing phase. At the beginning of the swing phase, the swing knee is bent. 400 ms after the start of the swing phase, the knee extension muscle is reactivated. Programmed in assembly, this amounts to about 30 lines of code.

In addition to this basic controller, a low power (< 1 Watt) Linux computer is mounted to the inner legs. This LART (Linux Advanced Radio Terminal)-board, developed at TUDelft, is implemented for onboard data acquisition and is not used for stability control.

The only sensing is the time of foot contact, used once per step. Taking account the implicit rounding from the processor loop time we estimate sensor information flow rate of about 6 bits per second.

**Cornell Biped with arms** This robot consists of two 0.8 m long legs attached at a hip joint, knees, curved-bottom feet, arms, and a small torso which is kept upright by connection to the legs with an angle-dividing mechanism. Each arm carries a battery. The right arm is rigidly attached to the left leg and *vice versa*, reducing yaw oscillations[11, 10]. The machine weighs 12.7 kg and has 5 internal degrees of freedom (one hip, two knees, two ankles). A latch at each knee passively locks the shank from swinging past parallel with the thigh and is released by a solenoid triggered by completion of the toe-off ankle extension. Toe-off restores energy lost to collisions. To minimize the needed motor size, energy for toe-off is stored in a compression spring between steps.

The thigh to shank length and mass ratios are 0.91 to 1 and 3.3 to 1, respectively. The electronics are in the hip/torso/head visible in Fig. 2c. A state machine with 8 binary inputs and outputs is implemented in 68 lines of code on an Atmel AT90S8515 chip running on an ATSTK500 standard development board. A second board with relays and passive conditioning components connects the board to the electromechanical and sensory parts. During the first state, Left Leg Swing, all actuators are unpowered and the left knee latch passively locks at knee strike. When switches below the left foot detect impending heel strike, the state switches to Right Toe-Off. This begins a timed activation of the solenoids that release the plantar-flexor spring of the right foot. When switches detect full foot extension, the state switches to Right Toe Return. During this state, a 9.5 Watt 6.4 oz MicroMo® motor is activated, retracting the foot and restoring spring energy. A timed activation of the solenoids then unlocks the right knee. When a switch on the motor indicates full foot retraction, the state switches to Right Leg Swing, and the motor is deactivated. The machine then swaps left and right legs and goes to the initial state. Taking all sensing, including the sensing of internal degrees of freedom which could in principal be made open loop, about 20 bits per step of information flows to the processor. The environmental sensing, the time of foot contact, is about one third of that. This machine is autonomous and thus has only one trick: walking forwards. Its speed, path and joint motions are not shaped or controlled but follow from the mechanical design and primitive toe-off actuation. Ankle extension occurs mostly after the opposite leg has completed the heel-strike collision. In principle the machine could be made to consume about 4 times less energy still by having toe-off before, rather than after, the opposing-leg foot-to-ground collision [19].

# References


[1] Y. Sakagami, R Watanabe, C Aorama, S Matsunaga, N Higaki, and K Fujimura. The intelligent asimo: System overview and integration. In *Proceedings of the International Conference on Intelligent Robots and Systems*, 2002. see also http://world.honda.com/ASIMO/.

[2] V. Radhakrishnan. Locomotion: Dealing with friction. *Proc. Natl. Acad. Sci. USA*, 95:5448–5455, 1998.

[3] E. Atzler and R. Herbst. Arbeitsphysiologische studien. *Pflg. Arch. ges. Physiol.*, 215:291–328, 1927.

[4] R.H. Rozendal N.H. Molen and W. Boon. Graphic representation of the relationship between oxygen-consumption and the characteristics of normal gait of the human male. *Proc. Kon. Ned. Akad*, 75:305–314, 1972.

[5] T. McGeer. Passive dynamic walking. *International Journal of Robotics Research*, 9:62–82, 1990.

[6] Flight and flying. In *Encyclopaedia Brittannica, 11th edition*, volume 10, page 514. Encyclopaedia Britannica, Inc, 1910.

[7] J. E. Wilson. Walking toy. Patent, Unites States Patent Office, 1938. Patent # 2,140,275 available from www.tam.cornell.edu/˜ruina/hplab/.

[8] Russ Tedrake, Teresa Weirui Zhang, Ming fai Fong, and H. Sebastian Seung. Actuating a simple 3d passive dynamic walker. IEEE International Conference on Robotics and Automation, 2004.

[9] M. Garcia, A. Chatterjee, and A. Ruina. Efficiency, speed, and scaling of two-dimensional passive-dynamic walking. *Dynamics and Stability of Systems*, 15(2):75–99, 2000.

[10] S. H. Collins, M. Wisse, and A. Ruina. A three-dimensional passive-dynamic walking robot with two legs and knees. *International Journal of Robotics Research*, 20(7):607–615, 2001.

[11] G. T. Fallis. Walking toy. Patent, Unites States Patent Office, 1888. available from www.tam.cornell.edu/˜ruina/hplab.

[12] Hurmuzlu Y. and Moskowitz G. D. Bipedal locomotion stabilized by impact and switching. part i : Two and three dimensional, three element models, part ii : Structural stability analysis of a four-element model. *International Journal of Dynamics and Stability of Systems*, 2(2):73–112, 1987.

[13] M. Coleman and A. Ruina. An uncontrolled toy that can walk but cannot stand still. *Physical Review Letters*, 80(16):3658–3661, 1998.

[14] Richard S. Sutton and Andrew G. Barto. *Reinforcement Learning: An Introduction*. MIT Press, 1998.

[15] W. Thomas Miller III. Real-time neural network control of a biped walking robot. *IEEE Control Systems Magazine*, 14(1):41–48, Feb 1994.

[16] M. Wisse, A. L. Schwab, R. Q. van der Linde, and F. C. T. van der Helm. How to keep from falling forward; elementary swing leg action for passive dynamic walkers. Submitted to IEEE Transactions on Robotics and Automation, 2004.

[17] A. L. Schwab and M. Wisse. Basin of attraction of the simplest walking model. In *Proc., International Conference on Noise and Vibration*, Pennsylvania, 2001. ASME.

[18] Richard S. Sutton, David McAllester, Satinder Singh, and Yishay Mansour. Policy gradient methods for reinforcement learning with function approximation. In *NIPS 1999*. Advances in Neural Information Processing Systems, 1999.

[19] A.D. Kuo. Energetics of actively powered locomotion using the simplest walking model. *Journal of Biomechanical Engineering*, 124:113–120, 2002.


**Supplementary information.** Videos of the robots walking can be found at the web site given in the caption of Fig. 2.


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