A Three-Dimensional Passive-Dynamic Walking Robot with Two Legs and Knees

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Abstract

The authors have built the first three-dimensional, kneed, two-legged, passive-dynamic walking machine. Since the work of Tad McGeer in the late 1980s, the concept of passive dynamics has added insight into animal locomotion and the design of anthropomorphic robots. Various analyses and machines that demonstrate efficient human-like walking have been developed using this strategy. Human-like passive machines, however, have only operated in two dimensions (i.e., within the fore-aft or sagittal plane). Three-dimensional passive walking devices, mostly toys, have not had human-like motions but instead a stiff legged waddle. In the present three-dimensional device, the authors preserve features of McGeer's two-dimensional models, including mechanical simplicity, human-like knee flexure, and passive gravitational power from descending a shallow slope. They then add specially curved feet, a compliant heel, and mechanically constrained arms to achieve a harmonious and stable gait. The device stands 85 cm tall. It weighs 4.8 kg, walks at about 0.51 m/s down a 3.1-degree slope, and consumes 1.3 W. This robot further implicates passive dynamics in human walking and may help point the way toward simple and efficient robots with human-like motions.

KEY WORDS—biped, passive dynamics, McGeer, robot, anthropomorphic, 3-D

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1. Introduction

It is natural to characterize an animal or a human's motion by the positions of its parts in time. Perhaps this is why the most common approach to building robotic walking machines, from 19th-century windup toys to the famous Honda Humanoid, is to control joint angles so as to mimic those of animals or humans. This trajectory-control approach to robotics has been called a "kinematic obsession" (R. Q. van der Linde, personal communication, 1999), and it often has a kind of rigor mortis as its negative consequence. Joints encumbered by motors and high-reduction gear trains, or their hydraulic equivalents, make joint movement inefficient when the actuators are on and nearly impossible when they are off.

From trajectory control, robotics has evolved to a more fluid and dynamic view by incorporating ideas such as "underactuation," "impedance control," and "equilibrium point" control. Nonetheless, many modern robots are kinematic (i.e., displacement controlled) at their core. The Honda Humanoid is the most familiar and successful of these and demonstrates that refinement of such an approach can yield smooth, versatile motions (Hirai et al. 1998). However, the Honda Humanoid does not move quite like people do and is energetically inefficient. For example, the 130-kg Honda P3 moves with a nonpendular appearance and uses about 2 kW during walking (Honda 2000), more than 20 times the muscle work rate of a walking human of the same size. Some part of this high energy consumption is due to friction, but a large part

is the consequence of a trajectory-based approach, especially when that trajectory is mostly limited to a sequence of static equilibrium postures.

Departing further from position-based control strategies are controllers that smoothly vary joint torque, allowing dynamics to control the details of the motion. For example, Jerry Pratt's two-dimensional walking robot, the Spring Flamingo, is a pleasing departure from the motion control paradigm. Although the Spring Flamingo's actuation is through computer-controlled, gear-reduced motors, it uses fast active force feedback to control torque rather than joint angles. This torque control allows the natural dynamics of the system to generate fluid-looking motions (J. Pratt and G. Pratt 1999; J. Pratt 2000).

A different approach to the imitation of animal and human motions focuses on minimizing actuation and control. Evolution may have favored efficiency and low demands on the neural system. A test of this concept is to see how well one can make a robot function with little actuation and no control. Obviously, humans and animals have some actuation and control, and so must all functional robots. Our approach to assessing the need for control is to see what is possible without it.

This control-free approach to robot design has its roots not in sophisticated path-following robots but in children's toys.

1.1. Ramp-Walking Toys

Simple two-legged ramp-walking toys have been around for at least a century (Bechstein 1912; Fallis 1888; Mahon 1914; Wilson 1938). Such passive toys (e.g., Fig. 1) should not be confused with locomotion toys that have windup or electric motors. Versions of the these toys, with either four legs or two legs and a training wheel, can be purchased for about $1 in many toy stores, but truly two-legged versions are available only as antiques. These biped "ramp walkers" travel down a shallow slope or are pulled by a string, and they walk in a somewhat stable, passive, three-dimensional gait. They are straight legged, so they must rock from side to side in order to lift their feet clear of the ground. They rely heavily on the static stability provided by large feet or a large mass hung below the walking surface. The devices we have seen take short steps that look unlike human motion and more like the waddling of penguins or ducks, which they are often designed to look like (see Extension 1[1]).

More recently, Coleman and Ruina (1998) and Mombaur, Coleman, and Ruina (2001) have demonstrated a variant that would rather walk than stand still. Their Tinkertoy walker has the apparently unique feature of being stable only when in motion. The Tinkertoy walker fails to imitate humans in that it has straight legs, depends on rocking for foot clearance, has a ridiculous mass distribution, and waddles much like the passive toys above (see Extension 2).

1. Please see the Index to Multimedia Extensions at the end of this article.

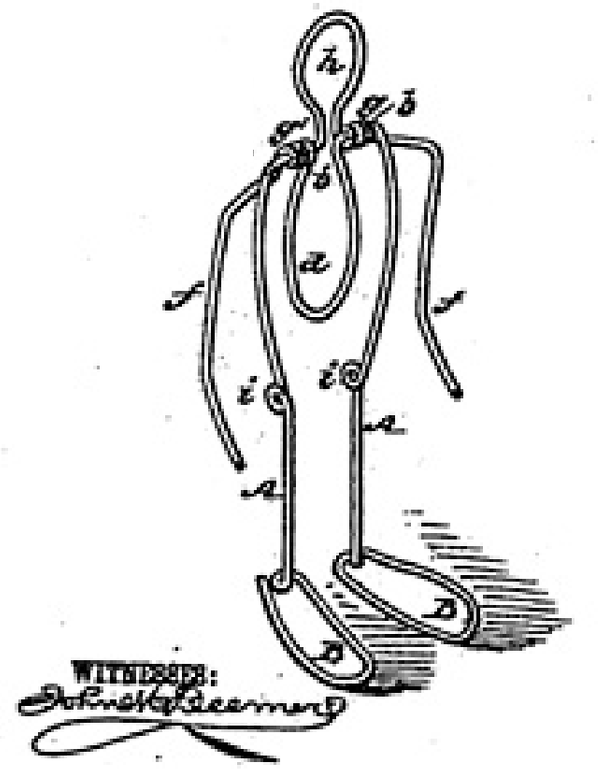

Fig. 1. Fallis's (1888) clever implementation of counter-swinging arms. The entire toy is made from two pieces of wire. Each wire makes up a leg, a bearing, an axle, and an arm. One wire also has a head and the other a body of sorts. Adelin Totilca made us a reproduction that takes rocking steps something like those described in the Fallis patent.

The waddling gait of these toys is a superficial inferiority that has obscured their dynamical similarity to dexterous animals until recently.

1.2. Passive-Dynamic Robots

Ramp-walking toys operate with principles described by centuries-old concepts, but their analysis and refinement has only been possible recently. This is because Newton's laws, as applied to such walking machines, are expressed as complicated nonlinear differential equations that can only be solved numerically using modern computers. Despite these complications, the passive-dynamic concept is quite simple: locomotion is mostly a natural motion of legged mechanisms, just as swinging is a natural motion of pendulums. Stiff-legged walking toys naturally generate their comical walking motions. This suggests that human-like motions might come naturally to human-like mechanisms.

A device operating passive dynamically can be efficient because it needs no energy for stabilization or control, only

power to recover small losses. The most fundamental cause of this energetic loss is impact, primarily between the feet and ground. In most passive-dynamic studies, power comes from the potential energy gained by moving down a ramp. Gravitational power is an easy-to-implement proxy for other simple low-power sources. In a sense, the passive-dynamic approach is the opposite of the trajectory control approach, which tends to constantly control actuation to force a system against its natural dynamic tendencies.

The modern incarnation of the passive-dynamic approach to locomotion was effectively invented by Tad McGeer. McGeer used the development of airplanes as inspiration. He noted that the Wright brothers mastered gliding first, then added a small amount of power to make successful powered airplanes. Passive-dynamic ramp walkers are the gliders of walking robots.

McGeer developed these free-motion designs using a nonlinear stability analysis based on numerical simulation of the Newton-Euler equations of motion. These studies led to his completely passive designs, implemented both in simulation and as walking machines built of bars and hinges. The McGeer machines have remarkably human-looking gaits, are more energy efficient than other walking robots, and are inherently stable with respect to small disturbances (see Extension 3).

However, McGeer's machines are impressively human-like only when viewed from the side. From the front, they look more like a person walking on crutches because they were built with four legs to keep the motion two-dimensional (Fig. 2).

McGeer (1991) also found an unstable, two-legged, three-dimensional, passive-dynamic biped in simulation. The periodic motions in these simulations had abnormally high yaw, and the numerically predicted instability presumably precludes physical realizability.

A logical next step was to make a three-dimensional machine with only two legs while maintaining the favorable traits of McGeer's four-legged versions. We describe such a machine here.

Fig. 2. An imitation of McGeer's (1990) design made by Yan Yevmenenko in our lab. It is a sturdier version of the one shown in Garcia, Chatterjee, and Ruina (2000) made by John Camp. The motion is constrained to two dimensions by the four legs.

Fig. 3. Our two-legged, kneed, passive-dynamic walking robot. The counter-swinging arms are attached rigidly to their opposing legs. Note that the right arm swings forward and out as the left leg swings forward.

2. The Present Device

Our device (Fig. 3) is conceptually similar to McGeer's (1990) original machine (see Garcia, Chatterjee, and Ruina's 2000 working imitation in Fig. 2). To preserve fore-aft (pitch) stability, the basic design is close to what one would get by cutting the four-legged machine in half. The resulting device is no longer as constrained as the former device, creating an important difference: new degrees of freedom and new ways to fall down. Thus, we had to change our design to keep it stable in three dimensions.

The new problems are unstable side-to-side lean and yaw. By "side-to-side lean," we mean rotation about an axis in

the direction of travel, called "roll" in aeronautics. "Yaw" is rotation about a vertical axis and is also called "steer" or "heading."

The four most important ideas that distinguish our two-legged, three-dimensional, kneed, passive-dynamic robot from its four-legged, two-dimensional, kneed ancestors are as follows:

1. Foot bottoms shaped to guide lateral motion;
2. Soft heels to reduce instability at heel strike;
3. Counter-swinging arms to negate yaw induced by leg swinging;
4. Lateral-swinging arms to stabilize side-to-side lean.

These ideas were developed through physical insight, experimentation, and lessons learned from previous passive walkers, as described below.

2.1. Foot Shaping to Guide Side-to-Side Lean

Because one foot is off the ground some of the time and the feet are not planted on a central line, the robot will fall from side to side if the center of mass is not moved left and right over the feet. One way or another, all two-legged walkers must have side-to-side motion of some kind.

Some walking devices have a rather free side-to-side rocking motion, including the spherical-foot Wilson Walkie (Wilson 1938) and the disk-foot Tinkertoy (Coleman and Ruina 1998). In contrast, Bechstein's (1912) patent (Fig. 4a), as well as Fallis's (1888) patent (Fig. 4b), has foot bottoms that guide the side-to-side lean as the foot rolls along the ground. Because these toys do not have knees, they depend on their side-to-side motion for ground clearance. Even though our device has knees that provide ground clearance, we use feet that guide the side-to-side motion in an attempt to enhance lean and yaw stability.

To minimize yawing motions, we wanted to have the largest possible frictional torques with a given foot size. Thus, we designed the foot with two side-by-side rubber-coated rails (Fig. 5). The intent is for the foot to maintain contact with the ground at two points, one on each rail. Each rail is approximately elliptical, and the inner rail has a smaller radius of curvature and protrudes below the outer rail. As the foot rolls along the ground, the shape of the rails causes the robot to sway from side to side; as the left foot rolls, the machine sways from vertical, to left leaning, and back to vertical.

Theoretically, these rails can be shaped such that the center of pressure is near the centerline of the foot during most of the time of foot contact. This would give the device a quasi-static lean stability. Furthermore, keeping the center of pressure in the middle of the foot maximizes the available frictional torque from the rails to resist yaw.

Interestingly, the simulations of Adolfsson, Dankowicz, and Nordmark (2000) predict that a device with feet that are only short overlapping line segments oriented orthogonal to the direction of travel might also work. This would roughly correspond to replacing each of our rails with a point contact.

2.2. A Soft Heel to Remove Collisional Indeterminacy

If stride length were known and remained constant, the feet could be designed so that the two rails of a striking heel hit the ground simultaneously. However, the heel-strike angle is neither exactly known nor exactly repeatable. Even if these were known, nearly simultaneous collisions of multiple points on a rigid body is a geometric singularity that causes indeterminacy in motion. That is, the result of the net collision for a rigid foot would be different depending on which point makes contact first, even if just barely first.

An example of this indeterminacy can be seen by dropping dice onto a flat surface. The outcome of the collisions is radically sensitive to the orientation of the cubes when they hit.

The collisional indeterminacy can be removed by making the contact compliant enough so that the collisional impact is not absorbed by just one rail. To prevent adding unnecessary degrees of freedom, we did not want to add compliance about the vertical axis or to up-and-down motions, so we used hinged foot arcs as shown in Figure 5f. Each arc is hinged at the toe with a pin orthogonal to the direction of travel. These arcs are connected together at their heels by a bar. The bar is hinged midway between the heels and is in contact with a stiff, damped spring. This foot design adds no vertical or yaw compliance.

As the foot rolls forward, the stiffness against sideways lean increases because the contact points move toward the pinned toes of the rails. We call this foot design a "soft heel." A machine built of real materials may have enough compliance without an explicit soft heel if the rail collisions are sufficiently close to simultaneous for the impulse to be distributed evenly.

2.3. Counter-Swinging Arms

The asymmetry of a two-legged design induces yaw. The straight-ahead walking of two side-by-side legs has angular momentum fluctuations about a vertical axis, which encourages a pirouetting motion of the robot. We did not want free yaw, so we countered yawing with friction at the foot rails (above). In our experiments, we found that these scrubbing torques were not sufficient to inhibit yaw. Therefore, we attempted to reduce the need for scrubbing torques by reducing the angular momentum fluctuations.

Elftman (1939) showed that arm swinging in human walking reduces the overall rotation of the body. Although probably more for appearance than mechanics, one of Fallis's toys

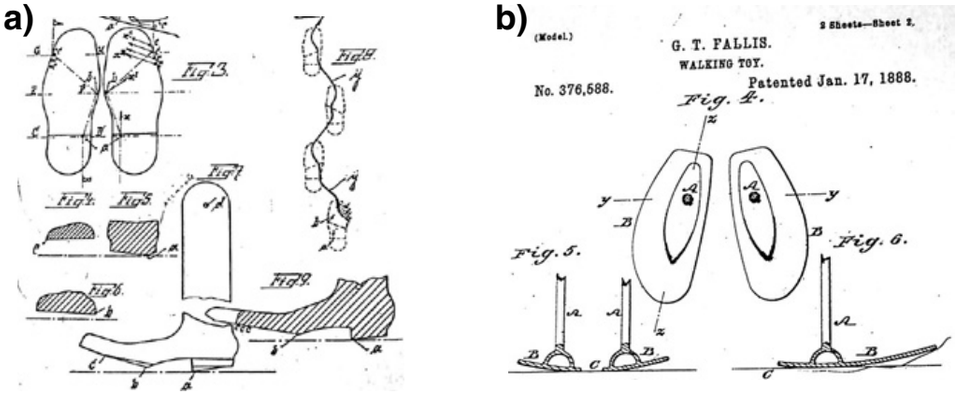

Fig. 4. (a) Bechstein's (1912) walking toy patent. The polyhedral feet are intended to guide the machine's side-to-side lean so that the center of pressure stays inside the footprint. (b) The Fallis (1888) patent that seems to use the same idea.

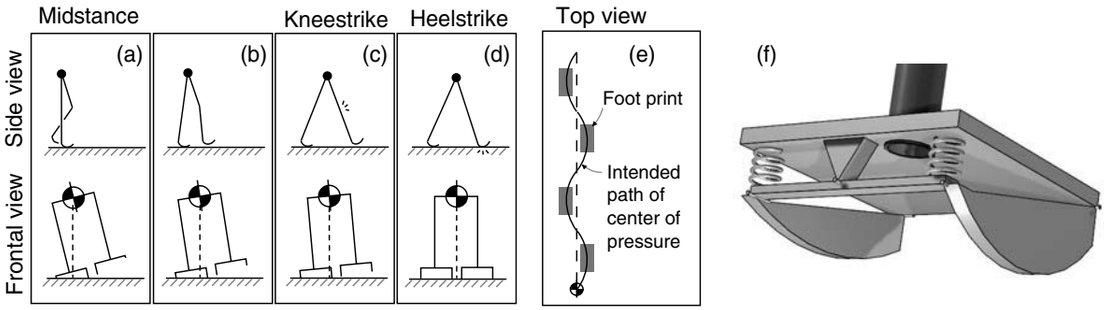

Fig. 5. **(a-d)** Side-to-side lean as guided by foot shaping. **(e)** Schematic of intended center of pressure path as a result of the side-to-side lean. **(f)** Schematic of the soft heel (left foot). The pivoting springs are at the heel. The asymmetric rubber-coated rails couple sideways lean to foot roll. The pivot and springs eliminate indeterminacies at the simultaneous impact of the two foot rails while maintaining stiffness against yaw and in the up-and-down direction.

also uses counter-swinging arms rigidly attached to their opposing legs (Fig. 1). Together, these ideas suggest that arms constrained to move fore and aft with the opposite leg might produce favorable changes in angular momentum fluctuation.

In our implementation, the arms are single rigid links with a large mass at their ends (see Fig. 3). They are pinned to always move within the same lateral plane as the thigh of the opposite leg. With counter-swinging arms and feet capable of providing frictional torque, the robot had a functionally stable heading.

2.4. Lateral-Swinging Arms

As shown in the unstable simulations of Kuo (1999), unconstrained side-to-side rocking can lead to instability. In fact, Kuo could not find a passive strategy for stabilization in his simulations. Moreover, early testing of our machine showed that it was either marginally stable or unstable in its leaning motions.

Lateral arm motion is one possible stabilizing compensation. Wisse, Schwab, and van der Linde (2000) suggested a free-swinging mass to balance the side-to-side sway of the legs. We chose to couple a lateral arm motion directly to the leg motion to keep the design simple (i.e., to not add any degrees of freedom).

The arms of the walker are attached to the legs such that they move in and out depending on relative thigh angle (Fig. 6). The left arm swings out as the right leg moves forward relative to the left. That is, both arms move left as the right leg moves forward and vice versa. Together with the counter swinging, the net motion of each "hand" is one from back and in to forward and out.

3. Simulation Was Not Used as a Design Tool

The four ideas above were implemented bit by bit with physical tinkering and little calculation.

Experience has given us strong lessons about the utility and futility of design using simulation. McGeer (1990, 1991) used simulation to find mass and geometry parameters for his

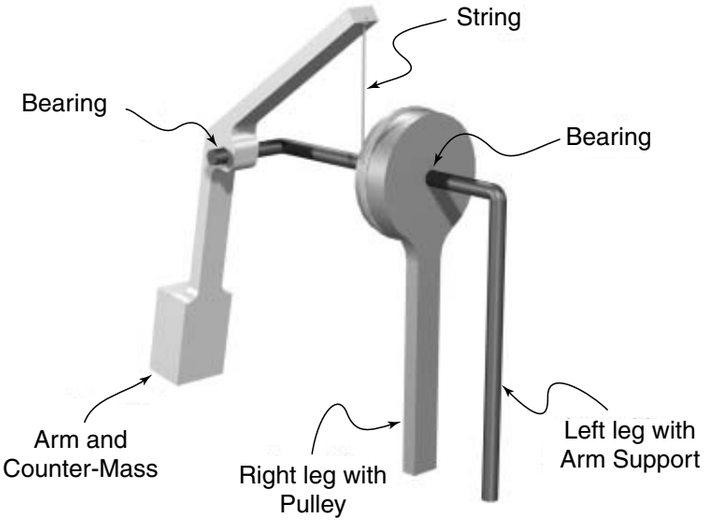

Fig. 6. Lateral arm swinging is coupled to the relative thigh angle using strings wrapped around the hip axle. The right arm swings forward and out as the left thigh swings forward relative to the right thigh. This is a schematic, not a design drawing.

two-dimensional walker. Similarly, Garcia, Chatterjee, and Ruina (2000) found simulation essential in order to duplicate that machine. On the other hand, months of simulation were not fruitful in finding the stable Tinkertoy design, which was ultimately found by tinkering. In fact, it was the successful physical model that motivated a more careful search for a stable simulation.

Because of the many effects in three-dimensional analysis that are difficult to characterize, whose importance we could not determine, and whose simulation is difficult (e.g., collisions, rolling, and scrubbing torques), we decided to forgo three-dimensional analytic modeling of this robot. We speculated that the mass properties of the four-legged design should work reasonably well in our two-legged device, and that we would use trial, error, and correction to minimize three-dimensional effects.

4. Evolution of the Physical Model

We present a brief outline of the design's progression.

4.1. Initial Design

We built a two-legged device with feet based on the guided rail and soft heel ideas described above and with mass and length parameters predicted to be stable by a two-dimensional analysis.

With a few weeks of tinkering, the device walked the full length of a 5-m ramp (see Extension 4). Inspection of the videos of this device showed substantial yaw and sideways leaning that were not intended. For instance, the device would sometimes pivot on one stance rail. The gait had a visually appealing swing but was not robust; it only walked the full length of the ramp twice.

4.2. Development of Yaw Compensation

As implemented at first, our walker depended solely on scrubbing friction to oppose yaw. Unfortunately, this was insufficient.

Moving the legs inward to reduce the moment arm was not sufficient to decrease the hip torque to a level controllable with friction. Instead, it significantly increased side-to-side lean instabilities, so the legs were returned to their original positions.

We attempted to add lean flexibility to the ankles to achieve better contact with the ground and, hence, more torque to resist yaw. The feet were then too floppy, and the device did not walk in a stable manner. Additionally, we found that even with this better ground contact, friction could not fully inhibit yaw.

We gained intuition for this yaw problem by suspending a crude model of the walker (with locked knees) from a point between its hip hinges. An attempt to counter swing the legs of such model induces extreme yaw as the legs pass through bottom center, as is expected from conservation of angular momentum about a vertical axis. When appropriate counter-swinging arms were added to this model, yaw was essentially eliminated. Counter-swinging arms added to our two-legged robot also successfully reduced yaw in its walking motions.

A schematic of the counter-swinging mechanism is shown in Figure 6 (see Extension 5).

At this stage, side-to-side rocking increased from step to step, leading to topple after several steps.

4.3. Development of Side-to-Side Lean Compensation

We removed the intentional soft heel because it was overly compliant with the added mass of the arms (arms account for 30% of the total mass) and seemed to cause instability. Changing to solid foot arcs regained some side-to-side lean stability, and even without the soft heel there seemed to be enough compliance in the foot to prevent collision indeterminacy of the type described earlier.

We then allowed the arms to swing freely laterally. In our implementation, the joints had very high friction, which made their lateral motions heavily damped. This seemed to allow useful dissipation of side-to-side rocking energy and improved the lean stability sporadically, but it was not robust.

We observed that human arms move in and forward simultaneously while walking naturally, so we added a mechanism to imitate this in-and-out arm motion. Amusingly, this configuration led to immediate toppling. Yet, it showed that lateral arm movement could influence lean stability. We reversed the mechanism to move the arms outward as they moved forward and adjusted the arms' constraints slightly until the design finally walked in a stable manner. A schematic of the string-wrapping mechanism is shown in Figure 6 (see Extension 5).

5. Results

A robust steady-state motion was found in the physical model. On a good day and with a practiced hand, the present two-legged passive walker walks steadily in about 80% of launches. Inappropriate initial conditions seem to be the primary cause of failed launches. The device walks the full length of a 5-m ramp without walking off the side in about 15% of launches.

The best slope seems to be about 3.1 degrees. The device weighs 4.8 kg and stands 85 cm tall. The center of mass is about 61 cm above the ground. Although the feet are not circular, they have a representative radius of about 12 cm, so the device is far from being statically stable either with one foot on the ground or when standing with parallel legs. The stride length is about 30 cm, the period of one full oscillation is about 1.2 seconds, and the walking speed is about 0.51 m/s. The gravitational power consumption is about 1.3 W. This extrapolates to about 34 W for a 130-kg device of the same size. In these trials, the nondimensionalized speed of $v/\sqrt{g\ell} = .18$ is a somewhat slow ramble compared to a person with a 1-m leg walking at 1 m/s with $v/\sqrt{g\ell} = .32$. The stance angle is about $2\arcsin(.15/.85) = 20$ degrees.

The walking motion is more pleasing to watch than that of any other walking robots we have seen (see Fig. 7, as well as Extensions 6 and 7).

However, the robot is obviously not human-like in a number of ways. It is missing upper body parts and degrees of freedom. The shoulders are coincident with the hips. The leg swinging is planar, which keeps the foot falls unnaturally wide. The wide feet and stiff ankle are obviously unnatural. Power comes from gravity, with no ankle extension or torques to accelerate leg swinging, which affects the device's motion. Even within our limited design parameters, the best-functioning arm motions are backward compared to anthropomorphic motions (out and forward instead of in and forward) for reasons we do not know in detail. With all of these shortcomings, it is surprising that the motion still looks so natural by today's robotics standards.

5.1. Remaining Problems

The walker needs a better mechanism to prevent bounce after knee collision. The current suction-cup method (McGeer 1990) has worked, but occasionally there is bounce and occasionally the knee lock still holds at the start of swing. The present string-wrapping method of regulating the lateral arm motion is not sufficiently adjustable for the evolution of a better linkage between leg and arm.

The device often does not hold its heading well. We do not know whether this is due to imprecision in construction or perhaps a heading instability of the type discussed in Adolfsson, Dankowicz, and Nordmark (2000).

Our three-dimensional design represents the results of trial and error starting with a well-understood two-dimensional design. As in natural evolution, it is possible that some useless traits have been maintained or that the design is non-optimal in various regards.

5.2. Future Work

Most obviously, an internally powered device that could walk on level ground, based on passive dynamics and thus minimally controlled and actuated, would add further credibility to passive-dynamic design concepts.

6. Conclusion

We have built the first two-legged passive walking machine with human-like motions, thus demonstrating that such a machine is possible. The primary challenges in moving from two-dimensional to three-dimensional walking were stabilization of yaw and side-to-side lean.

Although this robot has surprisingly human-like motions, we cannot claim that these all come from human-like mechanical design. Nor can we claim that our design is the only

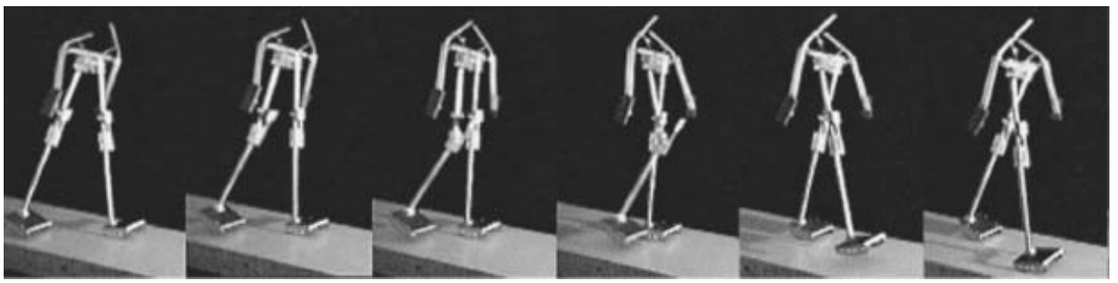

Fig. 7. A sequence of photos of our machine walking. The images were taken at a rate of about 7.5 frames per second (every fourth image from a video camera).

or even the best design for these motions. Rather, the success of this passive-dynamics design at achieving human-like motions shows the range of possibilities of passive-dynamic principles. We think of this success as an advertisement for passive-dynamics principles in general, not for the specifics of the design. Similarly, the success of this design helps show how useful such general principles might be in nature.

Acknowledgments

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Index to Multimedia Extensions

Extension	Media Type	Description
1	Video	Penguin walking toy (Wilson 1938). The penguin toy waddles down a slight decline. The gait is typical of toys of this genre.
2	Video	Coleman's Tinkertoy walker (Coleman and Ruina 1998). Two versions walk with tiny steps down a small slope. The first version shown is able to walk on a wide flat surface, and the second is the original Tinkertoy walker. Neither can stand stably in any configuration.
3	Video	Garcia, Chatterjee, and Ruina's (2000) imitation of McGeer's four- legged passive walker. The device is shown walking down a ramp in Cornell's Human Power Lab under the supervision of Michael Coleman.
4	Video	Our first two-legged kneed walker before arms were added. This is one of two times that the armless version walked the entire ramp.
5	Video	Demonstration of the arm to leg movement coupling. The left arm moves backward and forward with the right leg and vice versa, and the arms move outward as they move forward.
6	Video	Our finished walking machine. The device walks the ramp twice, viewed from the front, under the supervision of Steve Collins.
7	Video	Our device walking the ramp two more times, as viewed from behind.

NOTE: The multimedia extensions can be found online by following the hyperlinks from www.ijrr.org.