Powered Bipeds Based on Passive Dynamic Principles

S. O. Anderson*, M. Wisse†, C.G. Atkeson*, J.K. Hodgins*, G.J. Zeglin*, B. Moyer‡
*Carnegie Mellon University, †Delft University of Technology, ‡University of Pittsburgh
soa,cga,jkh,garthz@cs.cmu.edu; m.wisse@wbmt.tudelft.nl; bmoyer@pitt.edu
www.cs.cmu.edu/∼soa/, www.dbl.tudelft.nl

***Abstract*— We describe three bipedal robots that are designed and controlled based on principles learned from the gaits of passive dynamic walking robots. This paper explains the common control structure and design procedure used to determine the mechanical and control parameters of each robot. We present this work in the context of three robots: Denise, the Delft pneumatic biped, R1, a highly backdrivable electric biped, and R2, a hydraulic biped. This work illustrates the application of passive dynamic principles to powered systems with significant control authority.**

***Index Terms*— Passive dynamic walking, biped, compliance, humanoid, bipedal walking.**

I. Introduction

Humans walk with a robust, natural gait that appears to require little effort for control. Several approaches to developing bipedal robots with these capabilities have been pursued, including the zero moment point approach [1], [2], the hybrid zero dynamics approach [3], virtual model control [4], central pattern generator-based walking [5], hand-designed walking gaits [6], and passive dynamic-based walking [7], [8]. Because approaches based on passive dynamics produce natural looking and efficient gaits, we believe that it is a promising point of departure for the development of human-like walking bipedal robots.

A major challenge in applying this approach is adding actuation and control authority. The original passive walkers performed their downhill walking motion without the need for actuators or controls [7], [8]. This approach resulted in highly efficient gaits, but limited versatility (they only walked at one speed for a given floor slope) and robustness (the floor needed to be flat and rigid). By adding actuators, the machines gain controllability but lose passiveness.

Why is passiveness important? The low energy requirement of passive motion is one reason. However, passiveness also results in compliance; the unactuated joints comply to disturbances from the environment. We believe that compliance is an important characteristic for robust control of underactuated systems. Although we use passive walking as a starting point, our main interest is in compliant gaits that can be realized in powered machines.

Compliance allows a system to control which state variables will be affected by disturbances, and in this way increase the stability of the system by directing energy into modes where the energy can be easily dissipated. A compliant walking machine that uses simple control laws to quickly generate reasonable responses to poorly characterized disturbances is the long term goal of this research.

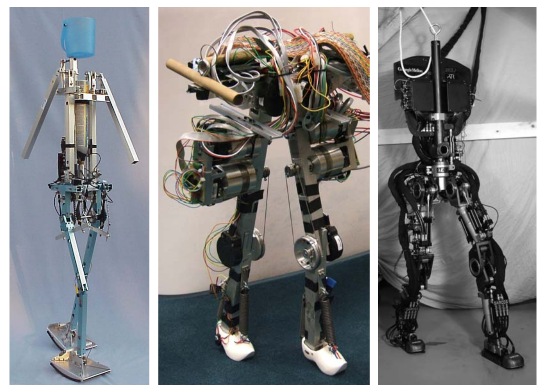

Fig. 1. Three powered biped robots shown in order of increasing actuation from left to right; Denise, the Delft pneumatic biped (left), R1, the CMU electric biped (middle) and R2, the Sarcos hydraulic biped (right).

For which degrees of freedom and in which phases of the motions is compliance desirable? We explore these questions by working with the Delft pneumatic biped Denise [9], with a new electric biped, R1, and with a new hydraulic biped, R2 (Fig. 1). For the two new robots, the first task is to obtain a gait that is similar to the passive-based gait of Denise.

In this paper, we describe how our experience in passive walking is applied to the two new robots. Section II briefly describes the robot hardware. The motivation behind our controller structure is set out in Section III, followed by a description of the walking results in Section IV. Section V provides a preliminary discussion on the role of passiveness and compliance in these walking motions.

II. Experimental robots

Pneumatic Biped Denise: The Delft pneumatic biped is an autonomous 3D robot weighing 8 kg and standing 1.5 m tall (Fig. 1). It has five internal degrees of freedom; one in each ankle, one in each knee, and one in the hip (Fig. 2). The ankles are somewhat unusual as they have a roll (lateral) degree of freedom but not a pitch (sagittal) degree of freedom [10]. Instead, the bottom of the feet are cylindrically shaped, following the arc foot shape of the original passive walkers. The lateral ankle joints have mechanical springs and damping but no actuation. The passive knees have mechanical stops to avoid hyperextension, and can be locked at full extension with

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a controllable latch. The hip has a single degree of freedom; a mechanical linkage couples the forward motion of one leg to backward motion of the other leg. A similar mechanism couples the arms to the same degree of freedom, although their low mass limits their effect on the dynamics. Two antagonist pairs of air-actuated artificial muscles, McKibben actuators, provide a torque at the hip joint to power the walking motion. The pneumatic control architecture only allows two states for the actuators; either the left leg or the right is pulled forward toward an equilibrium position while the other leg is on the ground. The actual leg motions are smooth due to the mechanical stiffness and damping of the actuators, which can be interpreted as a mechanical PD controller.

Electric Biped R1: The R1 biped (Fig. 1) is a 5.8 kg, 0.5 m tall planar robot with three degrees of freedom in each leg (hip, knee, ankle) (Fig.2). The robot is an improved version of a previous electric biped built at CMU [11]; it has stronger knees, new feet with ankle springs, and a lateral degree of freedom in the hips. This last improvement is not used in this paper and the motion of the robot is constrained to the sagittal plane by a tether boom.. The springy ankles help create a stable gait [12]. The hip joints are actuated by direct drive motors, and the knee joints are driven through a cable transmission mechanism with a low reduction ratio of three. These transmission mechanisms provide high backdrivability at the joints.

Hydraulic Biped R2: The R2 biped (Fig. 1) is a Primus lower body, a 3D human scale robot designed and built by Sarcos [www.sarcos.com]. It has seven actuated degrees of freedom in each leg and two in the torso for a total of sixteen degrees of freedom (Fig. 2). Each degree of freedom is driven by a linear hydraulic actuator with a flow control servo valve and a force sensor between the actuator and the joint. Each foot is equipped with a six axis force/torque sensor. We have increased the size of the feet in these initial experiments to 0.2 by 0.2 m. We placed material on the corners of the bottom of the feet that absorbs energy at heel strike and has a high coefficient of friction. The size of the robot is 0.77 m from hip joint to ankle joint, 0.17 m between the hip joints and 0.39 m from hip to knee. The robot weighs approximately 52 kg. The majority of this mass is located in the legs, while the upper body is relatively light. The robot uses a flexible umbilical to provide hydraulic and electrical power as well as communication to external computers.

III. Controller design

In these initial experiments we manually design the controllers. The controller is a state machine with two states, left swing and right swing. During both states the joints are servoed toward a trajectory that is a function of time. These trajectories of desired positions are the same each step, unless otherwise stated.

Many control architecture features are common to all three robots. First, each degree of freedom is controlled almost entirely locally–the only input to a joint's controller is that joint's state, the current time, and binary foot contact signals. Second, each robot uses swing leg retraction [15] and a

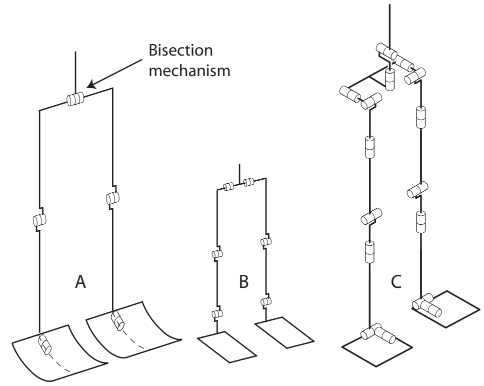


Fig. 2. Degrees of freedom for the three robots. (A) Denise has lateral ankle joints, knee joints, and a single degree of freedom in the hip. (B) R1 is constrained to two-dimensions by a boom. It has three degrees of freedom per leg. (C) The Sarcos biped has seven degrees of freedom per leg plus two in the waist.

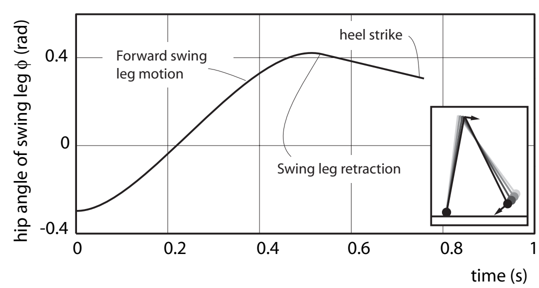


Fig. 3. Swing leg retraction; the relative hip angle decreases at the end of the step.

compliant ankle joint, features which we believe increase stability through compliant motion. Third, the 3D bipeds, Denise and R2, both exhibit smooth and slow motion of the swing leg as a result of our method for reducing yaw torques and producing lateral stability.

A. Sagittal motions

Swing leg trajectory: Controller design for each robot began with the creation of swing and stance leg trajectories. First, the foot of the swing leg must travel from push off to the correct pose for heel strike without contacting the ground. This requires coordination of the hip, knee, and ankle trajectories. Second, the swing leg trajectory ends by retracting the swing leg (i.e. moving the swing foot closer to the stance leg) during the time period in which heel strike is expected to occur (Fig. 3). We believe that a slight swing leg retraction increases gait stability [15] because when the robot is traveling faster than normal, heel strike occurs sooner and the step length is longer, while heel strike occurs later and the step length is shorter for slower velocities. Because longer steps have impact angles further from vertical, they dissipate more energy during heel strike and slow the robot down.

For Denise, these trajectories were a result of the passive mechanical properties of the legs and the McKibben muscles, which were switched on or off once per step. The body was mechanically constrained to bisect the angle between the thighs. In R1 the upper body is controlled to the bisecting angle of the two legs using both of the hip actuators, mimicking Denise's mechanical linkage. This control scheme was implemented with a PD controller where the set point is switched once per step to bring the new swing leg forward. Relatively low gains result in a smooth swing leg motion followed by a similar leg retraction phase.

The controller for R2 is more complex, but shares the two state control structure with Denise and R1. The trajectories for the hips and knees are based on fifth-order splines to create smooth trajectories and continuous accelerations. The knot points were adjusted by hand to create motions similar to those observed in Denise and R1.

Stance ankle: While in stance, the ankles of R1 and R2 behave like torsional springs. A stiffer ankle improves the walking robustness [12] much like larger arc feet improve the robustness of rigid-ankle passive walkers like Denise [14]. However, higher ankle stiffness also makes it more likely that the front or back edge of the foot will lift of the ground, creating problems with yaw control (Section IIIC). If the equilibrium point of the ankle is at the mid-point of the ankle's range of motion during the stance phase, then the maximum offset from the equilibrium point is minimized. This setting allows the ankle stiffness to be set to a higher value than if the equilibrium point is located elsewhere. However, if the equilibrium point is placed elsewhere energy can be added or removed from the system by work done at the ankle during stance. We choose an ankle stiffness for which the robot is statically stable while standing on both feet but does not lift the foot until push-off. In R2 we use an equilibrium point in the front half of the the range of motion (toes up), increasing the robot's forward velocity during stance.

In Denise this behavior was created by mechanically adjusting the arc shape of the feet because it has no sagittal ankle joints. R1's ankles are unactuated and mechanically tuned by changing springs. R2's ankles are controlled to mimic R1's ankle behavior.

Ankle push-off: Only R2 has the ability to use ankle push-off in its gait. It applies a constant ankle torque during push-off, adding energy to the system during each step [16]. The torque applied is limited by the need to keep the front foot in contact with the ground, and the range of push-off is limited by the lift-off of the rear foot as the body travels forward. The energy added increases as the range over which the ankle moves increases.

B. Lateral motions

The lateral motion should produce consistent and stable oscillations while keeping the feet flat on the ground [17]. In the 3D robots, this goal is achieved by heavily damping the ankle roll joints and tuning their stiffness and set point (either mechanically or via control). Our initial guess for the set point of each ankle is chosen such that the robot will balance on that ankle's foot while in a neutral pose. On R2 we found that tilting the outside edges of the feet up resulted in large lateral position offsets at mid-stance, while bringing the outside edges down increased the lateral velocity at heel contact.

For the 3D robots, coupling between lateral oscillations and dynamics in the sagittal plane can destabilize the gait. Because lateral and sagittal motion both affect ground clearance, each influences the position and timing of heel strike. As a result, gait modifications intended to stabilize the sagittal or lateral motion of the robot by altering the timing or placement of heel strike may also destabilize the motion in the other plane. For example, faster swing leg retraction increases the sensitivity of the step length to changes in the lateral oscillation. Likewise, increasing the torque used to stabilize the lateral dynamics may increase the variability in heel strike timing. We also found that ankle push-off tends to inject unwanted energy in the lateral oscillations.

C. Yaw

For the 3D bipeds, the most complex part of our design concerns yaw because rotation around the vertical axis affects many of the other components of the walking controller [18], [19]. Yaw is affected by the sagittal leg oscillations because the angular momentum of the legs around the center of mass varies as they swing fore and aft. Because of the low body to leg mass ratio of R2, this variation creates an oscillation in yaw. A second effect is that the vertical projection of the center of mass is not in line with the horizontal ground contact forces. This misalignment generates a yaw torque about the body. These two oscillations have opposite sign but in our experiments with R2 did not cancel out and yaw remains difficult to control. Yaw control can be achieved by minimizing the required torque and maximizing the available friction torque between the foot and the ground.

Minimizing required yaw torques: Making swing hip and knee trajectories smoother and slower reduces the rate of change of yaw angular momentum. Thus, the knee should bend as little as possible and the swing hip should move the leg forward slowly with minimal acceleration. These requirements compete with those of sagittal stability where a faster swing reduces the chance that the leg will not be in position for contact, and where a larger knee flexion angle improves ground clearance. Therefore, we have searched for the appropriate setpoints given this tradeoff.

Maximizing available yaw friction torques: The available friction torque is affected by the vertical force, the size of the feet, the foot sole material, and by the pressure distribution over the foot contact area. In order to utilize the full width of the feet for friction torques, the feet should be designed only to contact the floor at the edges. We keep the center of pressure away from the edges of the feet by clipping the torques that the ankle actuators generate. The tradeoff is between yaw torque minimization and lateral or sagittal balance; as argued earlier, a large travel of the center of pressure provides better lateral and sagittal stabilization. In our experiments, we found that we could let the center of pressure move fairly close to the sides of the feet, as the natural oscillations of walking keep the center of pressure away from the edge. Note that during push-off, rising onto the toes is not a problem, as the front leg is also in contact with the floor.

IV. Results

We report successful walking experiments with three different robots of increasing control complexity: the Delft pneumatic biped, the R1 electric biped and the R2 hydraulic biped. The gait characteristics are summarized in Table I and Fig. 4. The mean time between heel strikes for R2 was 0.84 sec, and the standard deviation in step duration was 0.043 sec. For R1 the average step duration was 0.56 sec with a standard deviation of 0.010 sec. The normalized step length and step durations for each robot are presented in Table I. The normalized step times for Denise and R2, the two 3D bipeds, are very similar and slower than R1's step time. We believe this difference is a result of the need to minimize yaw torques and the amplitude of lateral oscillations in three dimensions.

A. *Pneumatic Biped Denise*

The Delft pneumatic biped only requires one contact switch per foot for stable walking, there are no other sensors mounted on the robot. We collected gait data from Denise using a laboratory designed for recording human gait. This lab included a Vicon optical motion capture system and a pair of force plates embedded in the floor. Data collected using this system appears in Fig. 4A.

B. *Electric Biped R1*

R1 has joint angle information for all degrees of freedom except the ankle joint, plus an estimate of the actuator torques (motor current). The motion of R1's joints during gait is shown in Fig. 4B.

C. *Hydraulic Biped R2*

R2 provides 6DOF force-torque information in the foot in addition to pose and torque data. The motion of the joints controlled during gait is shown in Fig. 4C. As with R1, several important features of the gait discussed in Section III are visible in this plot. Hip retraction can be seen in the negative slope of the hip joint position at heel strike. Ankle push-off is visible in the left leg (thick line) ankle pitch trace between 0.1 and 0.4 seconds. Following push-off the ankle retracts for ground clearance, then extends to decrease the foot inclination at heel strike. The graph of ankle roll shows that the body swings laterally during the initial portion of stance, then returns before the next foot strikes the ground. Finally, to reduce yaw, the knee accelerations are minimized such that the knee moves as slowly as possible while still ensuring ground clearance and full extension at heel strike. The gait has a nearly straight knee during stance.

The bottom graph of Fig. 4C illustrates the ground reaction forces applied to the bottom of the feet during normal gait. Because the sensors are located in the feet, the data is expressed in foot coordinates. Stance for one leg begins with a rapid increase in reaction force corresponding to heel strike, then quickly drops to a value well below the static loading on a single stance foot as the opposite foot pushes off from the ground. The next section of the stance phase consists of a nearly constant reaction force close to the weight of the robot. During this time the robot's body and swing leg are moving forward, past the stance leg. Stance ends when the opposite heel strikes the ground, causing a sharp reduction in reaction force followed by a moderate increase due to push-off. Push-off completes when the foot leaves the ground and reaction force falls to zero.

TABLE I

GAIT CHARACTERISTICS. STEP LENGTH IS NORMALIZED BY LEG LENGTH l AND STEP TIME IS NORMALIZED BY $\sqrt{l/g}$.

	step length	step time
Delft pneumatic biped	0.46	3.0
R1 electric biped	0.58	2.7
R2 hydraulic biped	0.50	2.9

The trajectory of the center of pressure under the stance foot during gait is illustrated in Fig. 5. Initially the center of pressure is at the back outside edge of the foot as the ankle complies with the ground reaction force to bring the foot into flat contact. Once the foot reaches flat contact the center of pressure moves to the front of the foot for the remainder of stance as the robot pushes the body back onto the other foot and goes through toe push-off. At the end of push-off, the contact is on the front inside edge of the foot as the body tips toward the new stance foot.

At the end of the swing phase the R1 hip briefly reverses direction as the knee hits the mechanical stops. Because the robot is 2D, there is no need to minimize knee and hip accelerations in order to constrain yaw torques. The knee and hip have very high accelerations to increase ground clearance and prepare for heel strike. The knee also shortens more than with R2.

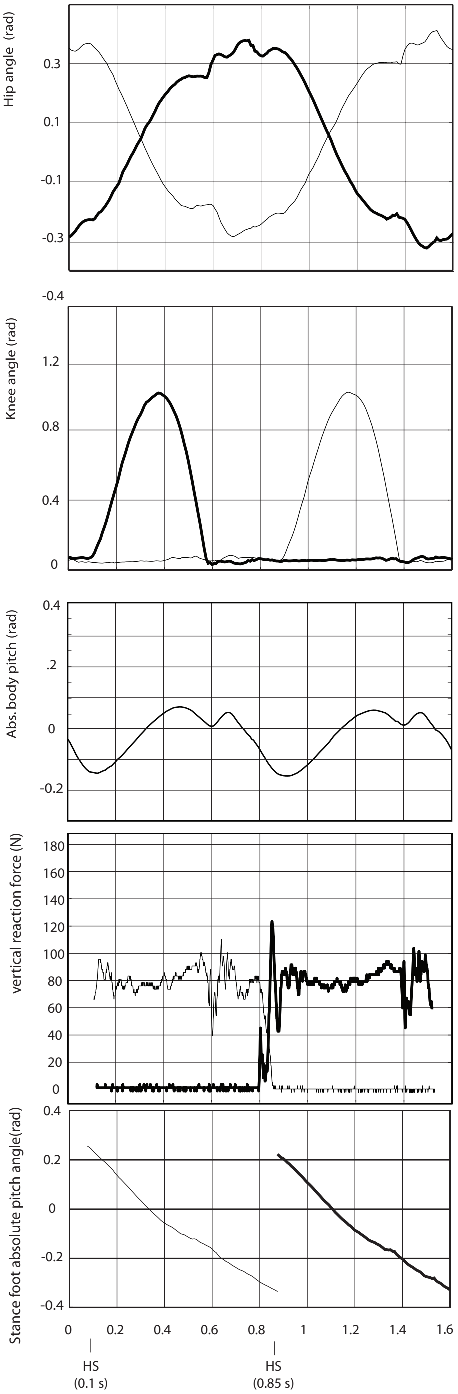
R2 exhibits less overall body motion than R1. R1's control mimics the bisection mechanism used in Denise. However, when we developed the controller for R2 we abandoned this control strategy because it produced large motions in the upper body that we believed were destabilizing. Instead, we created an upper body trajectory which attempted to minimize upper body motion.

V. DISCUSSION

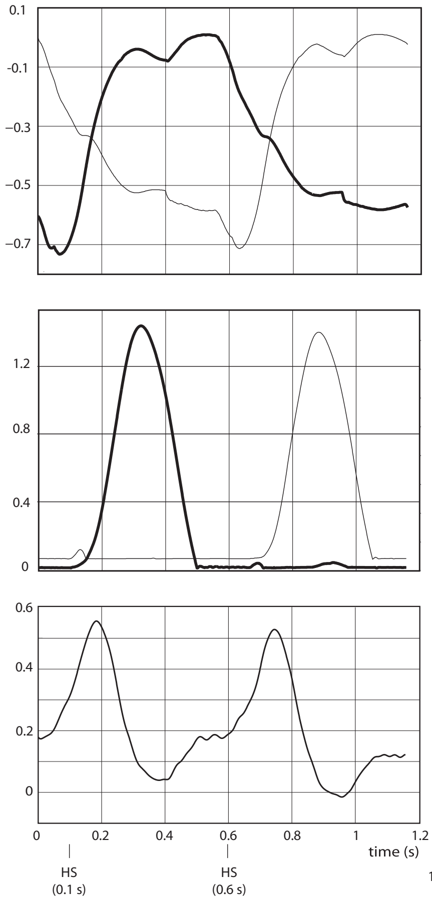
A. *The role of compliance*

We set out to study the role of compliance throughout the gait cycle. Here we report some preliminary observations that will guide our future research.

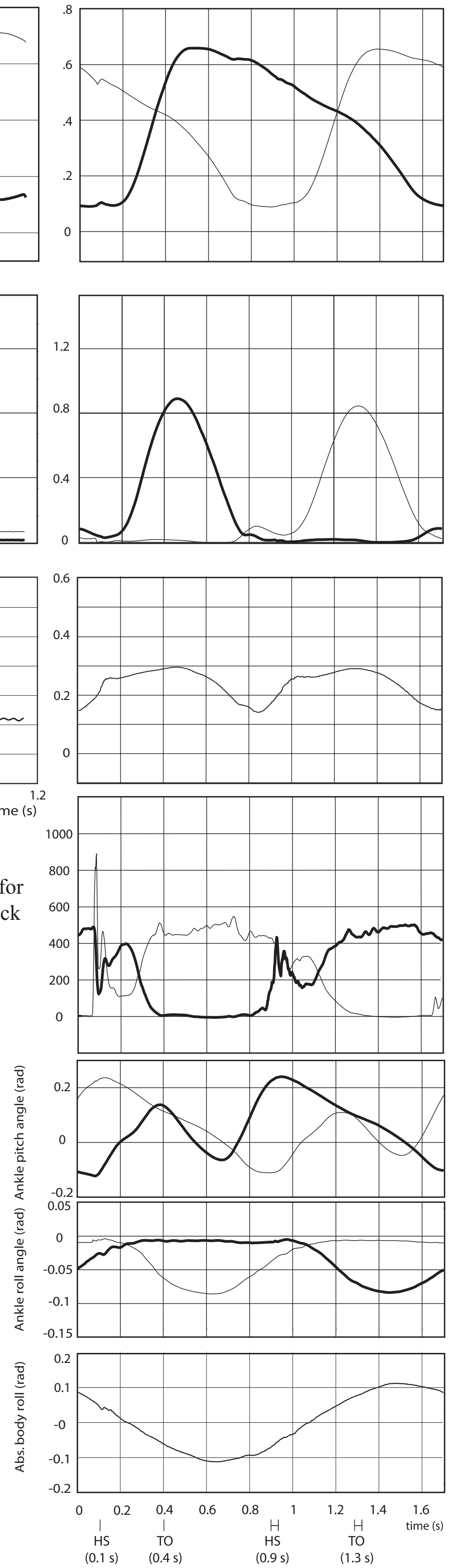
Swing leg trajectory: The motion of the swing leg is almost fully passive in Denise and in R1, yet it is barely passive in R2. The swing leg trajectories, however, are very similar; they all provide sufficient ground clearance, they all have a stabilizing swing leg retraction phase, and most importantly Denise and R2's trajectories consist of smooth motions to minimize dynamic coupling effects on the robot. One could argue that a passive motion is beneficial for energetic efficiency, but this benefit is highly machine-dependent. For example, the passive-like swing leg motion for R2 is dominated by the dynamics of the hydraulic drive system rather than by its rigid body dynamics. Yet, in our search for a successful walking motion, we converge to a motion quite similar to that of the other walkers. These results suggest that the actual trajectory of the swing leg, rather than the mechanism used to produce that trajectory, is the determining factor in stable gait. Thus,



4A. Hip, knee, body pitch, and stance foot absolute pitch angle, as well as ground reaction forces for two consecutive steps for Denise. The ankle has no pitch joint, but the feet have a cylindrical shape so they roll on the floor in the (forward) pitch direction. The thick line corresponds to the left leg.The ground reaction forces were measured with two force plates; the right footstepped on the first plate and the left foot on the second. Force data collected when more than one foot contacts a force plate has been deleted.



4B. Hip, knee, and body pitch angles for two consecutive steps for R1. The thick line corresponds to the left leg.



4C. Hip, knee, body pitch, vertical forces in the frame of the feet, ankle pitch, ankle roll, and body roll for two complete steps of R2. The lines are the average values over 20 steps. The thick lines illustrate the left leg's motion.

it appears that a passive or compliant swing is not a strong prerequisite for successful walking.

Stance ankle: In agreement with other biped robot research, we found that it is important to maintain flat contact between the foot and the floor, in order to provide sufficient yaw friction torque. Therefore, the stance ankle angles (pitch and roll) must be driven by the overall body motion. This observation suggests that compliance in the stance ankle is key to successful walking. The required compliance can be obtained either through control (as in R2) or with passive components (as in R1). We hypothesize that the dynamic effect of passive springs at the sagittal ankle joints of R1 and R2 is comparable to the effect of the arc shape of the feet of Denise.

Ankle push-off: During R2's double stance phase, the two legs form a closed kinematic chain with the floor. The forward leg is firmly planted on the floor, and the forward motion of the walker is mostly a result of the momentum from the previous step. Therefore, the elongation of the rear leg due to ankle push-off must be compatible with the overall body motion. For this reason we chose force control rather than position control for ankle push-off.

Body: Our results with R1 seem to indicate that passivity in the body (i.e. in the stance hip) is undesirable. If the stance hip is compliant, then the heel strike impacts have a strong effect on the body posture. The extra forward momentum due to heel strike must be corrected during the start of the next step, inducing oscillations and variability. We obtained our best results when controlling the body as tightly as possible. With Denise the body was even rigidly connected to the bisecting angle of the two legs, effectively giving it no degree of freedom at all. For R2, the body's angle relative to the stance leg was specified by a trajectory which we designed to minimize the body's rotation.

Hip ab/adduction: Thus far, all our experiments have been performed without any hip motion in lateral direction. In the frontal plane the machines are effectively rigid from the stance ankle up. Therefore, we cannot make any conclusions about whether compliance is useful for this degree of freedom.

B. Slow gait

For our 3D walkers (R2 and Denise), the stable gait is slower than for 2D walkers. It appears that a low stepping frequency is required to find stable lateral motions. We suspect that this requirement is due to the interaction between the ankle roll stiffness (that is limited to prevent sideways foot tipping) and the inertia of the robot. One reason for this behavior is probably the fact that we keep the lateral degrees of freedom in the hips locked at all times; the robot is essentially a rigid object slowly rocking side to side on its feet.

C. Future work on the robot R2

The umbilical attached to R2 includes two SAE-8 hydraulic lines. These hoses exert significant loads on the robot's torso. Dealing robustly with the dynamics of these hoses is a concern that we intend to address in our future work. We would like the robot to be as insensitive as possible to the handling of the hoses and able to pull the hoses autonomously.

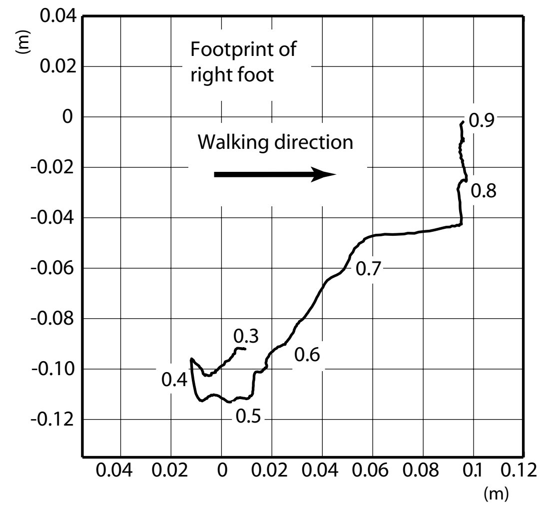


Fig. 5. Motion of the center of pressure in the right foot. The size of the graph represents the size of the foot.

We are currently operating at 1200psi hydraulic pressure for safety reasons. As we develop confidence in our control software and safety procedures, we will increase operating pressure to 3000psi. Operating at low pressures causes the internal dynamics of the actuators to have a greater effect on the behavior of the robot. In particular the maximum knee velocity during swing is limited, and some joints do not have sufficient torque capabilities in certain configurations.

VI. Conclusion

This paper explored how to make fully actuated robots walk like passive dynamics walkers. Controllers for a backdrivable electric robot and a force controlled hydraulic robot were designed based on the dynamic behavior of a passive dynamic walking machine powered by actuators at the hip. Key principles of passive dynamic walking that were used included swing leg retraction and compliant ankles. The next step in this research is to add compatible control laws that greatly increase the robustness and flexibility of walking.

Acknowledgments

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