Ballistic Control for 2D/3D Pneumatic Actuated Walking Robots[*]

Koh Hosoda[†‡] and Takashi Takuma[†]
[†]*Department of Adaptive Machine Systems, Graduate School of Engineering, Osaka University*
[‡]*Handai Frontier Research Center, Osaka University*
2–1, Yamadaoka, Suita, Osaka 565–0871, Japan
hosoda@ams.eng.osaka-u.ac.jp
takuma@er.ams.eng.osaka-u.ac.jp

***Abstract*— Walking is a complex behavior that emerges from interaction between the agent body and the terrain. To realize adaptive dynamic walking by an artificial agent, therefore, not only its body and control dynamics but also the dynamics of the terrain should be taken into account. In this paper, we propose a ballistic controller for pneumatic actuated walkers that only applies driving force in a limited period of time to utilize the dynamic property of the robot body. Feedback is designed based on the ballistic control, whose parameters are derived by estimation through experimental trials, to take the dynamics of the terrain into account. The proposed method is applied to two pneumatic-driven walkers: a 2D walker and 3D walker. Experimental results show the effectiveness of the proposed method.**

***Index Terms*— biped walking, pneumatic actuator, passive dynamic walking**

I. INTRODUCTION

The parameters of existing biped robots concerning to statics and kinematics such as link length, range of joint movement, required static torque are determined based on the kinematic and static balance analyses. The other parameters concerning to dynamics are design arbitrarily, such as link mass, center of gravity, inertia. A standard way to control such a biped robot is (1) to design desired motion of each leg assuming that the terrain is known, (2) to derive desired motion of joints based on the inverse kinematics, and (3) to apply position based control to track the desired joint trajectory. Since the analyses are only based on the kinematics, the trajectory of each leg is designed independently to the dynamics of the terrain. Therefore, the robot will be unstable when the kinematic model of the terrain is incorrect or the impact between the leg and the terrain is more than quasi-static. This may be one of reasons why most of the existing biped walkers are brittle against to the terrain disturbance.

There are several studies trying to realize efficient walking by designing not only the kinematics but also the dynamics of the walking robot. Passive dynamic walking [1], biped walking on an inclined slope without any actuation, is supposed to be a key to realize such energy efficient walking. There have been several studies trying to design controllers for such passive dynamic walkers to walk on a flat plane [2], [3], [4], [5], [6], [7], [8], [9], [10].

If the robot should be controlled to track given desired trajectories that are based on the kinematics, it is convenient to use electric motors with high reduction ratio. The inertial and reaction force will disturb the tracking control if the ratio is small. This may be the reason why electric motors with high reduction ratio are mainly adopted for the existing biped robots.

On the other hand, a pneumatic actuator is also one of the promising candidates for actuating biped robots since it can provide large force with a light mechanism, and since its elasticity will play a role to preserve and release the impact energy, which can enable energy efficient walking and running [11]. However, it is difficult to control its position precisely because of its complicated characteristics, time delay, hysteresis, and non-linearity. To realize biped walking by such actuators, Wisse and Frankenhuyzen designed the biped walker that can walk passively, and applied simple feedforward control without dealing with complicated dynamics of the actuator formally [7], [8].

Such simple feedforward control is enough as far as the biped robot walks within the stability margin provided by the well-designed body. To increase the adaptability, we may be able to apply feedback control based on sensory data. However, it is relatively difficult to derive a feedback scheme base on analytical dynamical model. If the robot is designed for passive walking, the joints are back-drivable, and therefore, the dynamics of the terrain and that of the pneumatic actuator are strongly coupled. Because of this coupling, it may be difficult to build an analytical model in which the terrain dynamics should be taken into account.

In this paper, we propose to take another way to derive a feedback scheme: to investigate the input-output relation of the real robot by several trials. We adopt a ballistic controller that only apples driving force in a limited period of time to utilize the dynamic property of the well-designed body. Owing to the well-designed dynamics of the robot, we can change the walking parameters in a certain range and store action and sensory data during walking. Consequently, we can acquire the relation between walking parameters and emerged

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walking behavior from walking trials. We have developed two biped robots, a 2D walker and a 3D walker with pneumatic actuators, and conduct experiments to show that the same design principle can be apply to different structures.

The remainder of this paper is organized as follows. First, we describe the design of a 2D walker, and investigate the input-output relation of the robot by several trials. We show several experiments on the proposed feedback control. Then, we describe a 3D biped walker, and discuss the applicability of the proposed method.

II. A 2D BIPED WALKING ROBOT WITH PNEUMATIC ACTUATORS

There have been several studies to apply little control for stabilizing the passive dynamic walker whose motion is restricted in 2D sagittal plane[2], [3], [4], [5], [6], [7] by having four legs instead of two. The robots developed in [4], [5], [6] did not have knees but utilize “step stones” or prismatic joints to let the leg swing without colliding with the terrain. Most of all studies adopted electric servo motors to drive the hip joints except [7]. If the electric motors are adopted, however, they have to adopt relatively low reduction gears to preserve back drivability of the hip joint to let the leg freely swing according to the gravity, which result in having bigger motors, e.g. direct drive motors. On the other hand, by adopting McKibben pneumatic actuators, this problem is easily avoided [7], [8]. In their work, the knee is not really driven by an antagonistic pairs of pneumatic actuators, but a actuator and a spring.

We developed a 2D robot with antagonistic pairs of pneumatic actuators shown in Figure 1. By this robot, we intend to investigate the relation between the elastisity of joints and that of the terrain. Therefore, all the joints are driven by antagonistic pairs of actuators, and every actuators are controlled by 5–port valves. 5–port ON/OFF electric valves enable us to take three positions: open to the atmosphere, close, and open to the supplied air pressure. This is an important hardware setting that can keep elasticity of a joint constant when the valve is “closed”.

Its height, width, and weight are 0.75[m], 0.35[m], and 5.0[kg], respectively. The robot has four legs two of which are connected to each other to prevent the robot from falling down sideways. Each leg has a knee. The length and weight of its thigh and those of its shank are 0.3[m], 2.1[kg], 0.35[m], and 0.5[kg], respectively. All the joints are driven by an antagonistic pair of McKibben muscle actuators [12] by Hitachi Medical Corporation [13]. The robot is equipped with (i) a micro computer (H8/3067) on the top, (ii) two CO_2 bottles as air supply, (iii) six 5–port ON/OFF electric valves for air supply and exhaust, and (iv) touch sensors on feet to sense the contact against the terrain.

In Figure 2, we show a control architecture for driving a joint. Each joint is driven by an antagonistic pair of the McKibben actuators each of which has a pressure sensor and supply and exhaust valves. Sensory data from the pressure sensors and potentiometers attached to the joints are sent to the micro computer via A/D converters. In experiments conducted in this paper, however, these data are not used online. The computer controls the supply and exhaust valves to rotate the joint. In the experiments, pressure of the supply air is 5[MPa] whereas that of the exhaust is atmospheric pressure.

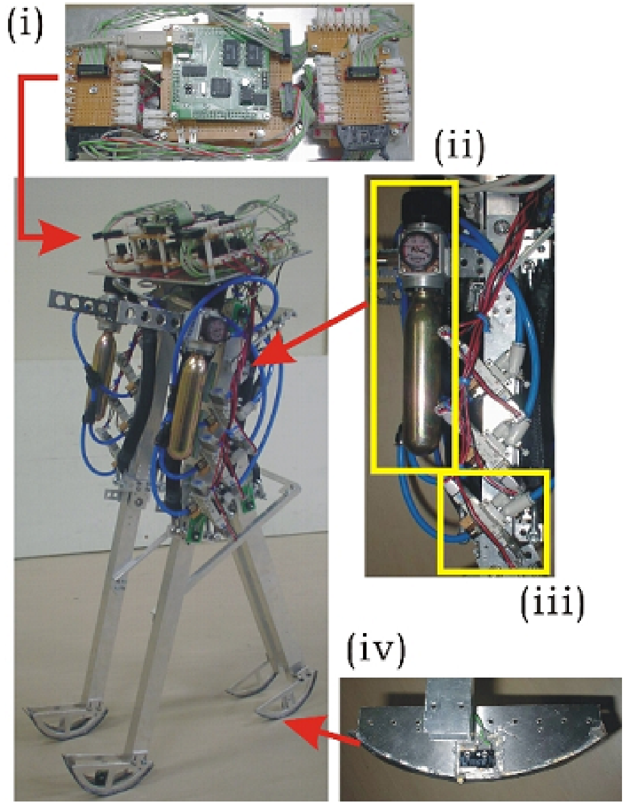

Fig. 1. A biped robot with pneumatic actuators: (i) a micro computer (H8/3067) (ii) two CO_2 bottles as air supply, (iii) six ON/OFF electric valves for air supply and exhaust, and (iv) touch sensors on a feet

III. BALLISTIC CONTROL FOR BIPED WALKERS

A. Ballistic control

Since the robot is designed appropriately for realizing passive dynamic walking, it can walk on a flat plane with a simple controller. To utilize the well-designed dynamics, we adopt a ballistic controller that only apply driving force in a limited period of time. Figure 3 shows the applied ballistic controller.

1. (1) For T_0[s] after a touch signal of a foot, all valves are closed, and the robot keeps the same posture. The robot moves ballistically according to the inertial force.
2. (2) After T_0 [s], the supply valve of the actuator of the hip joint that drives the swing leg is open to the supply pressure, whereas the exhaust valve of the antagonistic is open to the atmosphere for $S(k)$ [s]. The valves of the knee joint of the swing leg are opened and closed in an appropriate way so as to avoid the collision with the floor. Since the movement of the knee is small, the way does not strongly affect the behavior very much.

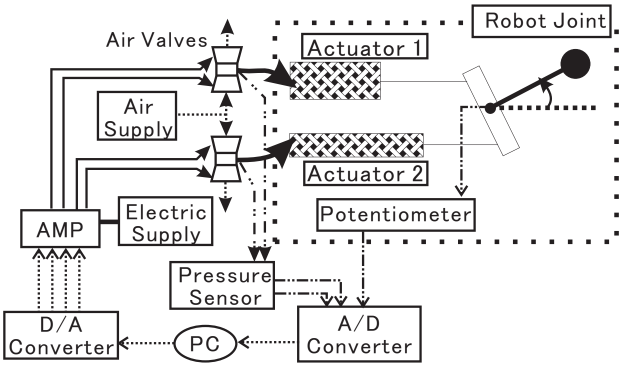

Fig. 2. A control architecture for driving a joint

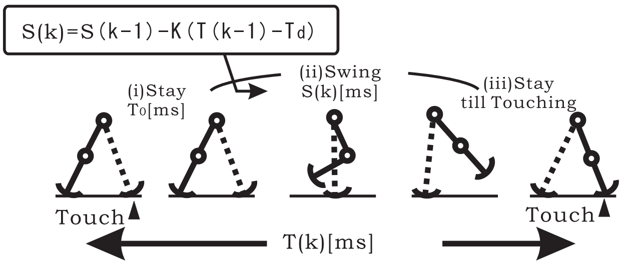

Fig. 3. Ballistic control for biped walkers

(3) $T_0 + S(k)$[s] after the impact, all the valves are closed again, and the robot waits for the next impact. In this phase, the robot moves ballistically according to the inertial force. When the impact is sensed, go back to the procedure (1).

B. *Identification of input-output relation*

By the ballistic controller described in the previous subsection, the biped robot can walk on a flat plane. Although the walking is robust within the stability margin provided by the well-designed body, it is still week against disturbance and modelling error. We should model the dynamics of the walking in some ways, and should apply feedback control based on the model to deal with them. Note that the model consists not only of the robot body but also of the terrain. If the robot is designed for passive walking, the joints are back-drivable, and therefore, the dynamics of the terrain and that of the pneumatic actuator are strongly coupled. Because of this coupling, it may be difficult to build a terrain model and a robot model separately. To realize biped walking based on passive dynamic walking, therefore, we need a new modelling scheme that models terrain dynamics and actuator dynamics altogether.

In this paper, we propose to investigate the input-output relation of the real robot by several trials. Thanks to the good dynamic property, the robot has a certain stable basin that we can change the walking parameters in a certain range. Therefore, we can acquire the relation between walking parameters and emerged walking behavior from walking trials.

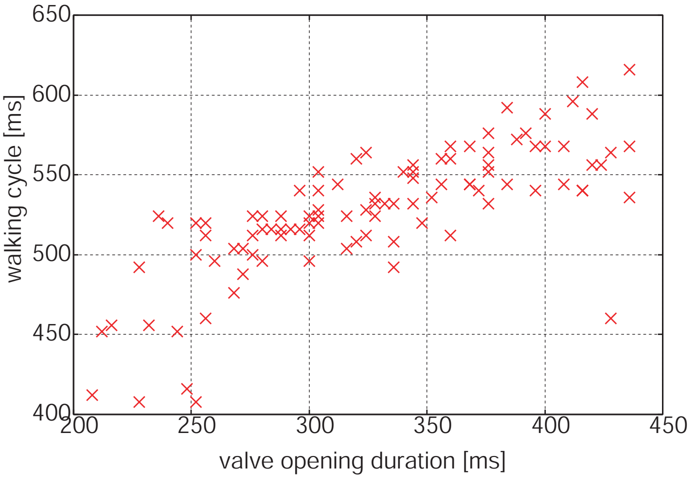

Fig. 4. The relation between the opening valve time $S(k)$ and walking cycle time $T(k)$

During walking by the ballistic controller, we change the valve opening time $S(k)$ from 200[ms] to 450[ms]. Figure 4 shows a clear relation, a positive linear relation between the valve opening duration $S(k)$ and the walking cycle time $T(k)$. By utilizing the relation, we can apply feedback control.

C. *Feedback control of cycle time*

We apply feedback control to make the walking cycle time $T(k)$ converge to a desired one T_d by changing the valve opening time $S(k)$ in every step:

$$S(k) = S(k-1) + K(T(k-1) - T_d), \qquad (1)$$

were K is a feedback gain constant. Note that this scheme is based on I–control. We also tested P–control, which was too sensitive and brittle against disturbance. We are analyzing the reason, but we still do not find the rational reason yet.

In this paper we chose $T_d = 560$[ms] according to the result shown in Figure 4. The feedback gain is selected empirically, $K = 0.3$. We show experimental results that the robot can walk down over a difference in level (Figure 5). The floor is made from urethane foam, and the difference is 9[mm]. The walking trajectory of each trial differs from those of others since the initial position and posture cannot be reproduced identically. Therefore, we run 100 trials, to validate the effectiveness of the proposed scheme in a probabilistic way. As a result, the robot can walk over the difference $82/100$ times with the proposed feedback controller, whereas $10/100$ times without it. This result tells that the proposed controller can deal with the disturbance provided by walking over the difference. In Figures 6 and 7, we show changes of the walking cycle without and with the controller. At the position of the difference, the walking cycle largely decreases, and the controller can deal with it to recover the walking cycle.

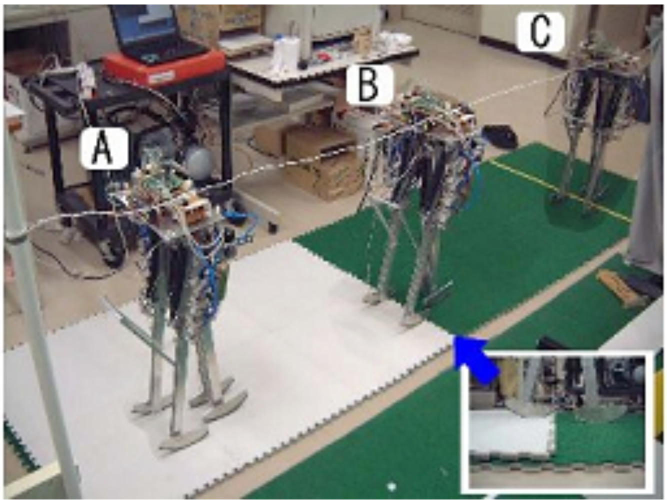

Fig. 5. The robot walks down over a difference 9[mm] in level on an urethane foam floor.

IV. A 3D BIPED WALKING ROBOT WITH PNEUMATIC ACTUATORS

To show the versatility of the proposed method, we intended to apply it to another 3D pneumatic actuated walking robot. There have been a few studies to apply little control for stabilizing the passive dynamic walker in 3D [9], [8], [10]. Tedrake et al. and Collins et al. applyed actuation only at the ankle joints, not at the hip joints to preserve the its passivity. Wisse adopted an antaginistic pair of McKibben pnematic actuators to drive the hip, which can realize active and passive states by the same mechanism. His robot Denise, only has actuators on the hip, not on the knees nor the ankles.

We developed a new 3D biped walking robot with pneumatic actuators shown in Figure 8. Its height, width, and weight are 0.83[m], 0.36[m], and 7.0[kg], respectively. The robot has two legs and two arms, therefore it can fall down sideways. Each leg is connected to the opposite arm. Overview of the structure of the robot is shown in Figure 9. It has totally 10 degrees of freedom: 2-DOF ankles, 1-DOF knees, 1-DOF shoulders, and 1-DOF hip joints. Each joint is driven by an antagonistic pair of McKibben muscle actuators. The acutators are connected to the 5–port ON/OFF electric valves that enable us to take three positions: open to the atmosphere, close, and open to the supplied air pressure.

The robot is equipped with a micro computer (H8/3067), 20 on/off electric valves for air supply and exhaust on the top. It has touch sensors on feet to sense the contact against the terrain. It has two CO_2 bottles on its arms for being autonomous, but these are not used in experiments in this paper.

V. APPLICABILITY OF THE PROPOSED METHOD

To validate the versatility of the proposed method, we again try to apply the same method to this walker. By the ballistic controller, the 3D biped robot can walk on a flat plane more than 16 steps, since it has certain stability margin provided by the well-designed body. A sequence of walking is shown in Figure 10

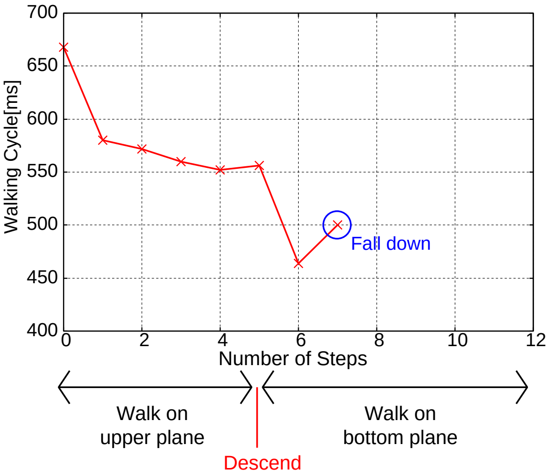

Fig. 6. Change of the walking cycle without the proposed feedback control: Because of the difference, large cycle change occured at the 5th step, and the robot fell down at 7th step.

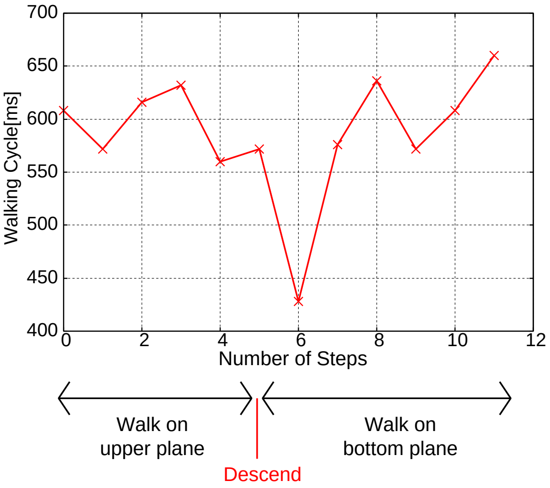

Fig. 7. Change of the walking cycle with the proposed control: Because of the difference, large cycle change occured at the 5th step, but the robot could recover from it.

We again model the dynamics of the walking in the same way, and apply feedback control based on the model to deal with disturbance and error. The relation between the valve opening duration $S(k)$ and walking cycle $T(k)$ is shown in Figure 11. Experimental trials are conducted 30 times for each opening duration, and error bars are shown in the figure. It also shows a clear relation, a positive linear relation between the valve opening duration $S(k)$ and the walking cycle time $T(k)$ like the 2D walker. By utilizing the relation, we can apply feedback control.

VI. CONCLUSION AND DISCUSSION

In this paper, we have proposed to utilize a ballistic controller that only apples driving force in a limited period of time to utilize the dynamic property of the well-designed

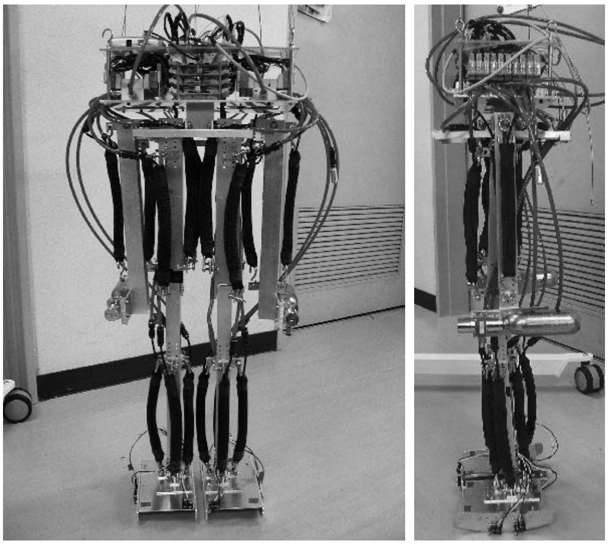

Fig. 8. A 3D pneumatic actuated walker driven by an external air compressor

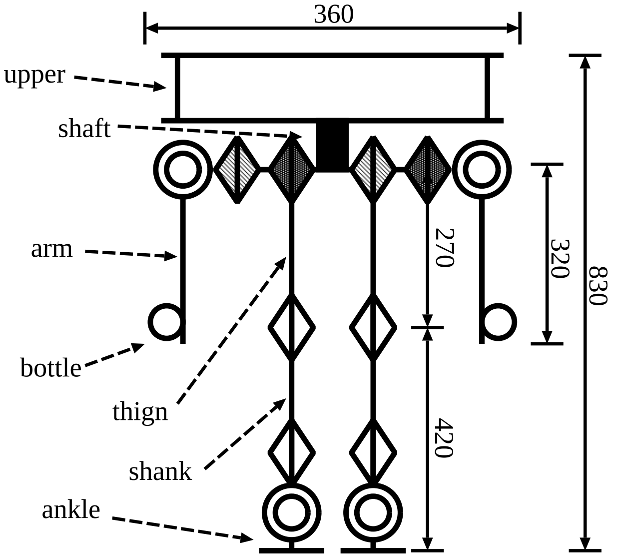

Fig. 9. A sketch of joints of the 3D pneumatic driven walker

body for controlling pneumatic driven walkers. Two types of walkers, 2D walker and a 3D walker with pneumatic actuators have been developed, and several experiments are conducted to show the effectiveness and versatility of the proposed method.

Since walking is locomotion, the foot positions always change, and characteristics of the floor also changes at every foot step. Also, the characteristics is affected by the dynamics of the walking robot. So far, such interaction between the walking robot and the floor is totally ignored by just kinematically modelling them. In real situations, however, such variation cannot be ignored. Moreover, if the robot is designed for passive walking, the joints are back-drivable, and therefore, the dynamics of the terrain and that of the robot are strongly coupled. From these reasons, it is not supposed to be appropriate to model the floor by a deterministic model like a spring/damper model that is often adopted in the simulator. We proposed a simple way to identify the relation between the valve opening time (the driving input) and the walking cycle (the output), and to apply feedback control by utilizing the relation. Since the interaction between the robot and its environment is not negligible to build an adaptive robot [14], we believe that the proposed scheme will open a new horizon to control walking robots.

Fig. 10. A motion sequence of walking of the 3D pneumatic driven walker

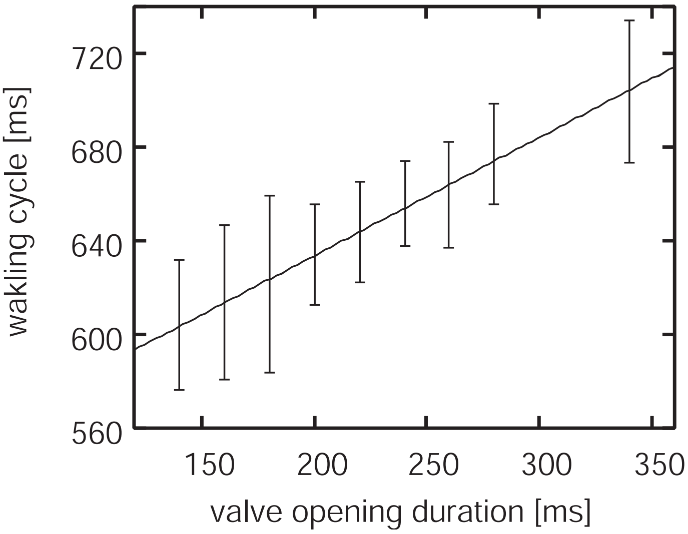

Fig. 11. The relation between the opening valve time $S(k)$ and walking cycle time $T(k)$ of the 3D pneumatic driven biped walker

In the experiments, however, how the elasticity of the knee joint affects to the walking performance is not clearly investigated. For the 3D walker, we found the fixed pressure for the ankles and knees to realize walking by trials. We should further do more experiments to investigate the relations. We can emphasize, at least, the hardware we developed is capable to do such experiments, and it is the first robot whose all joints are driven by antagonistic pairs of pneumatic actuators.

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