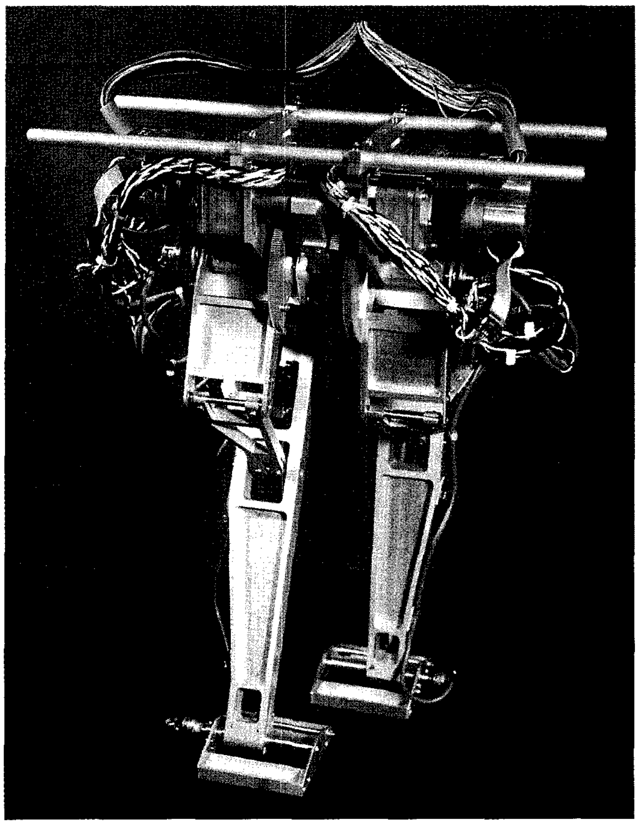
Experimental Study of Biped Dynamic Walking

Shuuji Kajita and Kazuo Tani

An experimental study of a biped robot is presented. A new scheme named the "Linear Inverted Pendulum Mode" is utilized for controlling a biped walking on rugged terrain. We developed a six-d.o.f. biped robot, "Meltran II," which has lightweight legs and moves in a two-dimensional vertical plane.

To investigate the effects not well discussed in the theory, we carried out two experiments, the support phase experiment and the support exchange experiment. The support phase experiment was carried out to check the actual dynamics of a biped walking under the proposed control. It was shown that the dynamics of the robot can be regarded as linear even though the mass of the legs, which was neglected in the theory, exists.

The support exchange experiment was performed to check leg support exchange. We found that a smooth leg support exchange is achieved by making the foot contact with a certain vertical speed and holding two-leg support for a certain short period. Based on these results, a whole biped control system was implemented. In our experiment the robot walked over a box of 3.5cm height at a speed of 20cm/s.



Introduction

Many studies of biped locomotion have been conducted worldwide [1-15]. One of the important subjects is how to generate trajectories for dynamically stable walking. This is difficult because a biped robot has high-order and nonlinear dynamics, which does not allow a general analytical solution.

Vukobratovic et al. discussed a numerical calculation of trajectories for biped dynamic walking [14] and later, Takanishi et al. realized a dynamic walking robot using a similar method [13]. Though their method worked successfully, such calculation took so long that a walking robot could hardly adapt to various ground profiles in real-time.

If the complex dynamics of a biped are simplified in some way, we can use a more efficient method to obtain the reference trajectory. For this purpose, Golliday and Hemami [2] used state feedback to decouple the support leg dynamics and the swing leg dynamics. Furusho and Masubuchi [1] used local feedback control to each joint and obtained a reduced order model.

On the other hand, it is known that a simple control method can be applied for a biped whose legs are massless or very light. Gubina et al. used a biped model with massless legs and simulated dynamic walking under a simple control law [3]. Miura and Shimoyama designed a biped robot with very light legs and demonstrated dynamically stable walking which was planned and stabilized by a simple algorithm [9]. Raibert developed a biped robot that ran based on his one-legged hopping machine [12]. His control law was designed by utilizing the feature of the light and springy leg.

Our idea is a combination of these two promising strategies, i.e., using a local feedback and a robot with lightweight legs. Fig. 1 shows an inverted pendulum consisting of a body with mass m and a massless leg of variable length r. Such a model can be recognized as a simple biped in a single leg support phase. In Cartesian coordinates its motion equations are represented as follows.

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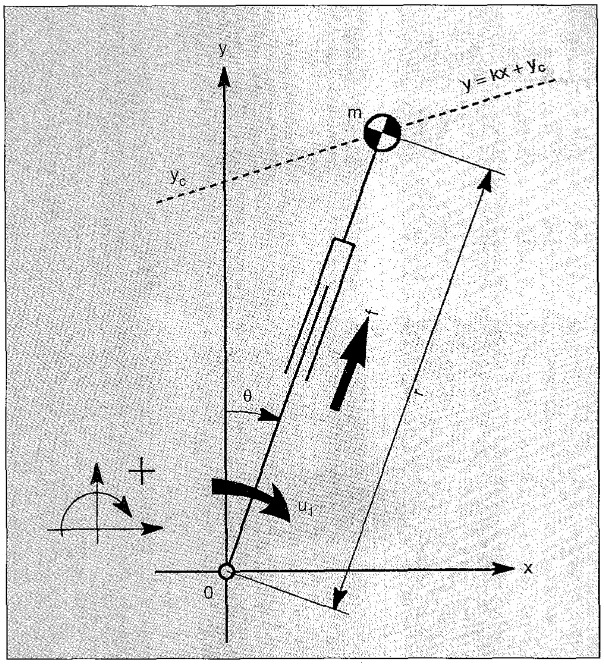

Fig. 1. Inverted pendulum and constraint line.

$$m\ddot{x} = \frac{x}{r}f + \frac{y}{r^2}u_1 \tag{1}$$

$$m\ddot{y} = \frac{y}{r}f - \frac{x}{r^2}u_1 - mg \tag{2}$$

where u_1 is the ankle torque, f is the kick force along the leg, and g is the gravity acceleration.

Let us assume the motion of the mass is controlled to move on the following "constraint line":

$$y = kx + y_c\,, \tag{3}$$

where k is the slope of the constraint line and y_c is its intersection with the y-axis. Combining Equations (1), (2), and (3) and eliminating the kick force f from these equations, we obtain the following equation:

$$\ddot{x} = \frac{g}{y_c}x + \frac{1}{my_c}u_1 \tag{4}$$

We call these dynamics the *Linear Inverted Pendulum Mode* and propose it for the design and control of a biped walking on rugged terrain [5].

Fig. 2 shows the basic concept of our walking control using the linear inverted pendulum mode. We assume the robot knows the profile of the ground before it begins walking. First, the robot decides the foothold positions for each step (shown by the triangles). Then, it calculates a constraint line (shown by the broken line) connecting the points at the same height y_c above these foothold points. While walking, the support leg is assumed to be changed instantaneously. Therefore, the body is supported by exactly one leg at any given time. In each supporting phase the robot controls the center of mass (COM) to keep on the constraint line and controls its body posture to remain vertical. These controls are executed by the knee and the hip joint of the support leg. Under such control, if all mass is concentrated on the body (i.e., the legs are assumed massless), the horizontal motion of the COM with respect to the supporting point is represented by Equation (4). Since Equation (4) does not contain the term of the slopes of the constraint line, the dynamics of each support phase are always the same, even when the robot walks up and down on uneven terrain. In this article, we describe how to implement the linear inverted pendulum mode on a real robot. There are two problems in applying our theory to a real biped robot. One problem is that the legs of a real robot have mass, but they were assumed to be zero in the theory. To learn what effect the leg mass has in the linear inverted pendulum mode, we carried out the *support phase experiment* detailed in the next section. In this experiment, the robot is controlled to stand on one leg and to keep its hip joint on the constraint line. The ankle joint of the support leg is then set free. Free motion is initiated by pushing the robot body by hand. By analyzing the trajectories, we estimated the horizontal dynamics of the real biped robot in the support phase.

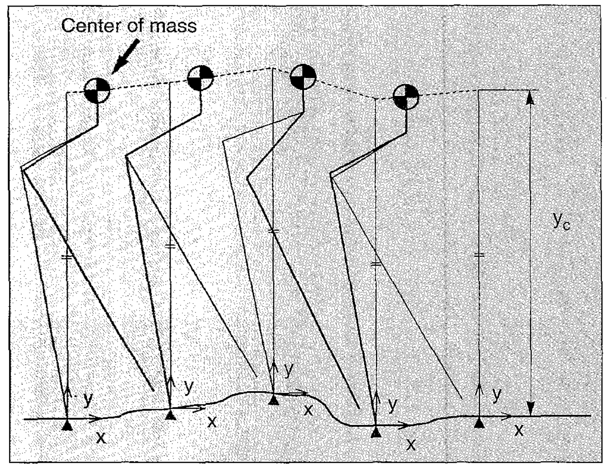

Fig. 2. Walking on rugged terrain.

The other problem in applying the theory lies in the support leg exchange. In our theory, we simply assumed that the body speed at the end of a particular support phase becomes the initial body speed of the next support phase across the support leg exchange. We therefore conducted an experiment to obtain adequate control for a smooth exchange. In this experiment, the robot is controlled to walk just a single step, that is, the robot exchanges leg support only once. By analyzing the horizontal motion after the exchange, we estimated how the speed of the body changes at the instant of the support leg exchange.

In the final section on experiments, we report on a biped walking on an uneven terrain using the control system based on the results of the support phase experiment and the support exchange experiment.

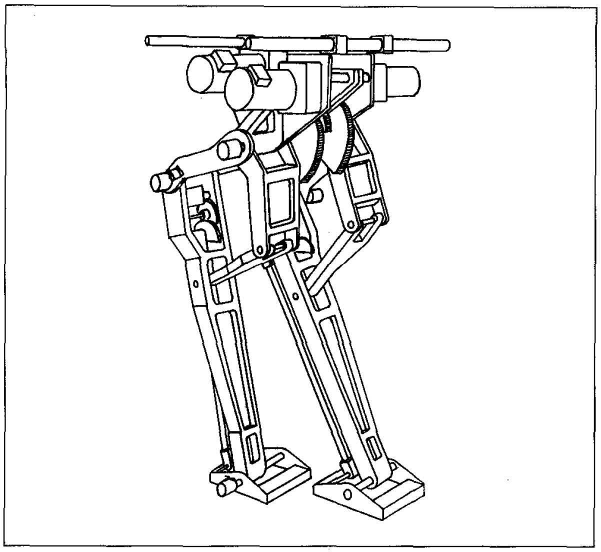

Fig. 3. Biped robot "Meltran II."

Mechanism of the Biped Robot

Fig. 3 shows our biped robot "Meltran II." Each leg is configured as a parallel link mechanism and is driven by two 11-watt DC motors mounted on the body. These motors are equipped with rotary encoders.

The ankle joint is driven by a 6.4-watt DC motor mounted on each leg. The ankle, knee, and hip joint of each leg have potentiometers to detect the angles between neighboring links. The walking motion is constrained in a sagittal plane by means of the laterally wide feet. Thus, all discussion in this article is about two-dimensional motion.

The parallel link design was adopted to reduce the weights of the legs and to emulate the massless leg model analyzed in our previous report [5]. However, the mass of the legs accounts for 47.4% of the total mass, so we can hardly regard them as massless.

Support Phase Experiment

Constraint Control Implementation

If the legs are massless, the center of mass (COM) of the whole robot would be the same as the COM of the body. In the case of a real biped, however, the legs are not massless. The COM of Meltran II exists near the hip joint, but it moves about ±1 cm according to swinging of the leg. To simplify the constraint control, the hip joint is controlled to move on the constraint line, rather than controlling the COM of the whole robot.

Fig. 4 shows the coordinate system for the control of particular step. As shown in the figure, we assume that the foot touches the ground with its toe and heel, and the angle α between the normal line of foot and the y-axis already known. To simplify the experiment, we used ground for which the foothold place is always horizontal ($\alpha = 0$).

The constraint line (constraint condition) is represented in Cartesian coordinates whose origin is on the ankle, with

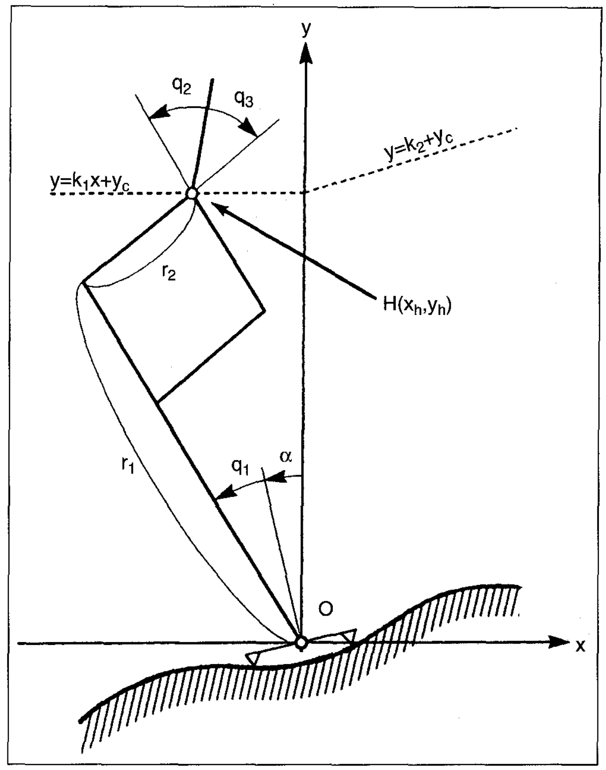

Fig. 4. Constraint control.

$$\begin{cases} y_h = k_1 x_h + y_c & \text{if } x_h \le 0 \\ y_h = k_2 x_h + y_c & \text{if } x_h > 0 \end{cases} \tag{5}$$

where (x_h, y_h) is the position of the hip joint H, k_1 and k_2 are the slopes of the constraint line, and y_c is its intersection with the y axis. As explained in the previous section, the slopes k_1 and k_2 are determined from the profile of the ground and changes step by step (k_2 of current step is the same as k_1 of the next step). On the other hand, y_c does not change throughout the walk. For all experiments in this article $y_c = 34$ (cm).

The constraint control was realized using simple inverse kinematics. We applied local position feedback to the joint q_2 and q_3 of the support leg. As the reference for this feedback, q_{2ref} and q_{3ref} were calculated as follows:

$$q_{2ref} = q_1 + \alpha \tag{6}$$

$$q_{3ref} = \gamma(q_1 + \alpha) - \beta \tag{7}$$

where

$$\gamma(q) = \cos^{-1}\left(\frac{r_1(k \sin q - \cos q) + y_c}{r_2\sqrt{1+k^2}} \right)$$

$$\beta = \tan^{-1} k$$

$$k = \begin{cases} k_1 & \text{if } x_h \le 0 \\ k_2 & \text{if } x_h > 0 \end{cases}$$

where q_1 is the angle of the ankle joint measured by the potentiometer of the supporting foot. The reference angles were calculated every 1 ms.

Experiment

The support phase experiment is an experiment to learn the horizontal dynamics of a real robot under the constraint control. The robot was controlled to stand on one leg and the constraint control of Equations (6) and (7) were applied. To examine the horizontal dynamics, we freed the ankle joint of the support leg (i.e., ankle torque $u_1 = 0$), and pushed the robot by hand to start its body moving on the constraint line. During this experiment, the posture of the swing leg was fixed. Fig. 5 shows a result of this experiment.

The horizontal displacement of the hip joint is calculated from the angles of support leg, q_1, q_2, and q_3, according to

$$x_h = r_1 \sin q_1 + r_2 \sin (q_1 - q_2 + q_3) \tag{8}$$

where r_1 and r_2 are the lengths of the links.

First, we determined the "balancing point," the point where the robot body moves neither forward nor backward, but stays in balance. We obtained $x_h \equiv x_{offset} \neq 0$ as the balancing point because the hip joint is not the real COM of the whole robot. Using this x_{offset}, we define x as the horizontal displacement of H to simplify the identification of the dynamics, in the manner

$$x = x_h - x_{offset}\,. \tag{9}$$

The solid lines in Fig. 6 shows six different trajectories of $x(t)$. We obtained a different trajectory in every trial because of the different initial speed imparted by hand.

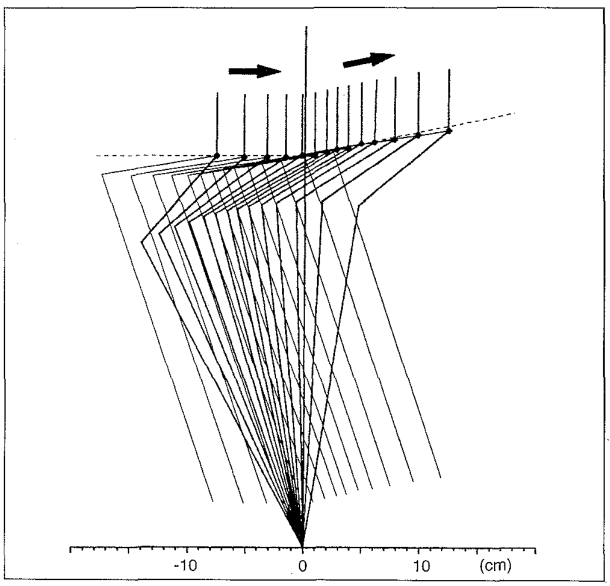

Fig. 5. Support leg experiment. Constraint: $y_c = 34.0$ (cm), $k_1 = 0$, $k_2 = 0.2$.

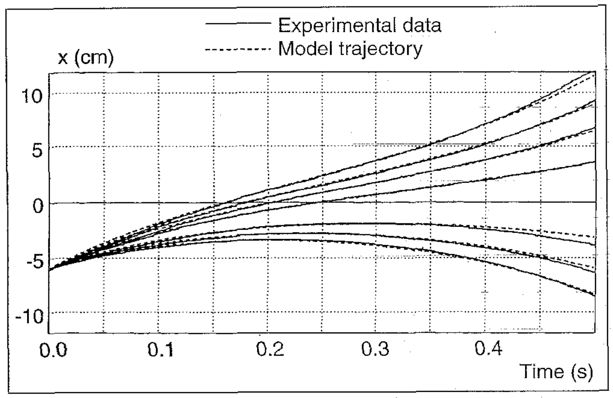

Fig. 6. Horizontal motion of the body. Constraint: $y_c = 34.0$ (cm), $k_1 = 0$, $k_2 = 0.2$. Estimated: $y_{exp} = 31.7$ (cm), $d_{exp} = 1.9$ (s^{-1}).

The experimental data can be explained by the following simple linear equation [6]:

$$\ddot{x} = (g / y_{exp})x - d_{exp}\dot{x} \tag{10}$$

The broken lines in Fig. 6 indicate the trajectories of Equation (10) calculated by curve fitting, and they correspond very well to the experimental data. From this curve fitting, we estimated the parameters $y_{exp} = 31.7$ (cm) and $d_{exp} = 1.9$ (s^{-1}).

In addition, we conducted another five sets of experiments using different slopes k_1 (= k_2) = -0.2, -0.1, 0.0, 0.1, 0.2. In all experiments, we also obtained a good correspondence between the experimental data and the linear model of Equation (10). Table 1 shows the estimated parameters from the experimental data. The important point to note is that y_{exp} and d_{exp} do not change remarkably with the slopes k_1 and k_2. From these results, we can conclude that the horizontal dynamics under the constraint control can be represented by the simple linear model of Equation (10).

Model Following Control

Though we carried out the support phase experiment fixing the joints of the swing leg, they must move in real biped locomotion. Since the swing leg motion influences the body motion as a disturbance, Equation (10) is no longer effective to predict the motion of a walking robot.

To guarantee a predictable motion of the robot, we apply a "model following control" using ankle torque u_1, which is an input force of the linear inverted pendulum mode as shown in Equation (4). u_1 is calculated as follows:

Table 1. Estimated Parameters of Support Phase

k_1 (=k_2)	y_{exp} (cm)	d_{exp} (s^{-1})
-0.2	31.8	1.5
-0.1	31.5	2.4
0.0	32.4	2.0
0.1	32.3	1.7
0.2	32.9	1.6
mean value	32.2 ± 0.5	1.9 ± 0.3

$$u_1 = k_P\left(x_{ref} - x\right) + k_D\left(\dot{x}_{ref} - \dot{x}\right) + k_I \sum \left(x_{ref} - x\right)\Delta t \qquad (11)$$

where

u_1 = ankle torque of supporting leg

Δt = sampling time (1 ms)

k_P, k_D, k_I = feedback gains for model following control

x_{ref}, $\dot{x}_{ref}$ = position and velocity of the reference trajectory

In this control, if the robot generated too large ankle torque, the sole of the support foot would lose contact with the ground and the constraint control would fail. Therefore, the absolute ankle torque $|u_1|$ must be limited according to

$$|u_1| \leq u_{max} \qquad (12)$$

where u_{max} is the maximum ankle torque. When u_1 is saturated by Equation (12), calculation of the third term of Equation (11) is stopped to avoid the wind-up phenomenon of the integrate term.

The term u_{max} can be approximated from the total mass of the robot m and the distance between the ankle and toe (or the ankle and heel) d as

$$u_{max} \simeq mgd\,, \qquad (13)$$

where g is the gravity acceleration. As the reference model for the model following control Equation (11), we used the following system:

$$\ddot{x}_{ref} = \frac{g}{y_m} x_{ref} \qquad (14)$$

The parameter y_m is determined according to the experimental result of Table 1, and

$$y_m = \bar{y}_{exp} = 32.2 \text{ (cm)}\,.$$

By this model following control, the viscous effects estimated in the previous section are canceled, and the horizontal motion of the support leg follows the solution of Equation (14).

Support Exchange Experiment

The support exchange experiment was performed to check and improve exchanges of leg support. Fig. 7 shows the setup for this experiment. The robot walks on an iron plate covered with a rubber sheet of 2mm thickness to prevent a slip of the supporting foot as the soles of "Meltran II" are bare aluminum surfaces. A laser displacement sensor unit (Keyence LB-300) was used to measure the horizontal motion of the body.

The control sequence of the support exchange experiment is as follows:

1. Stand with two legs.

2. Start of walking: Lift up foot1 (at 0.0s). Simultaneously, apply the constraint control to leg2 and apply the model following control to the ankle of foot2.

3. Support of leg2: The body moves horizontally following the reference model.

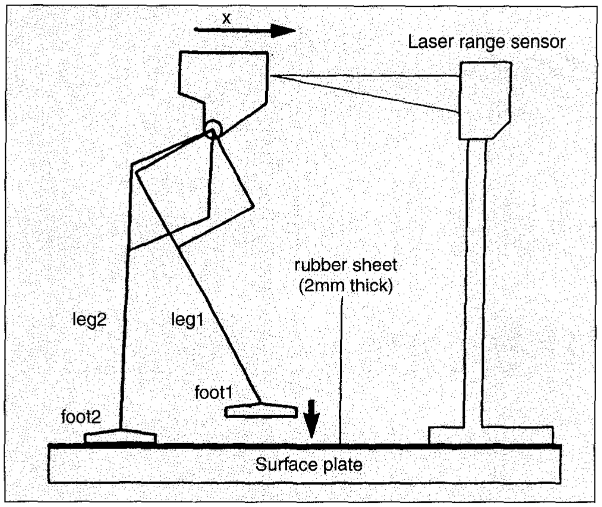

Fig. 7. Support exchange experiment.

4. Prepare for touchdown: Set foot1 down on the ground at 0.35s. Just prior to touchdown, stop the constraint control and model following control of leg2.

5. Support exchange: At 0.35s, apply the constraint control to leg1 and set the ankle torque of foot1 to zero. Lift up foot2 simultaneously.

6. Support of leg1: The body moves horizontally.

7. Prepare for finish: Set foot2 down on the ground at 0.7s. Just prior to touchdown, stop the constraint control of leg1.

8. Return to two-leg support.

The touchdown time 0.35s determines the support motion after the exchange. Roughly speaking, earlier touchdown results in slower walk and later touchdown results in faster walk. The touchdown condition for desired motion can easily be calculated from the ideal linear inverted pendulum mode [4].

Using the same touchdown time, we still observe a different body motion for each experiment because part of the horizontal speed of the body is lost at Step 5 depending on touchdown and lift-up patterns of the swing leg. We can estimate this speed loss by analyzing the horizontal motion that occurs during Step 6. For smooth biped walking, the difference between the horizontal speed just before the exchange and just after it must be as small as possible.

We carried out two sets of support exchange experiment using different touchdown and lift-up patterns of the swing leg. Each set of experiments was repeated 10 times under the same conditions. The upper graphs of Fig. 8(a) and (b) show the horizontal motion of the body as the results of the support exchange experiment. The solid lines and error bars indicate the mean trajectories and the standard deviations of 10 trials. The broken lines indicate the reference trajectories of the ideal robot whose dynamics are given by Equation (14). We calculated this trajectory assuming that the speed does not change at the instance of the support leg exchange. Comparing these two experiments, the body motion of Fig. 8(b) is more suitable for walking, because of its smaller loss of horizontal speed.

The lower graphs of Fig. 8(a) and (b) shows the foot touchdown speed in each experiment. Solid lines and dash-dotted lines indicate the foot touchdown speed patterns of foot1 and foot2, respectively. In experiment (a), foot1 was controlled to touch-

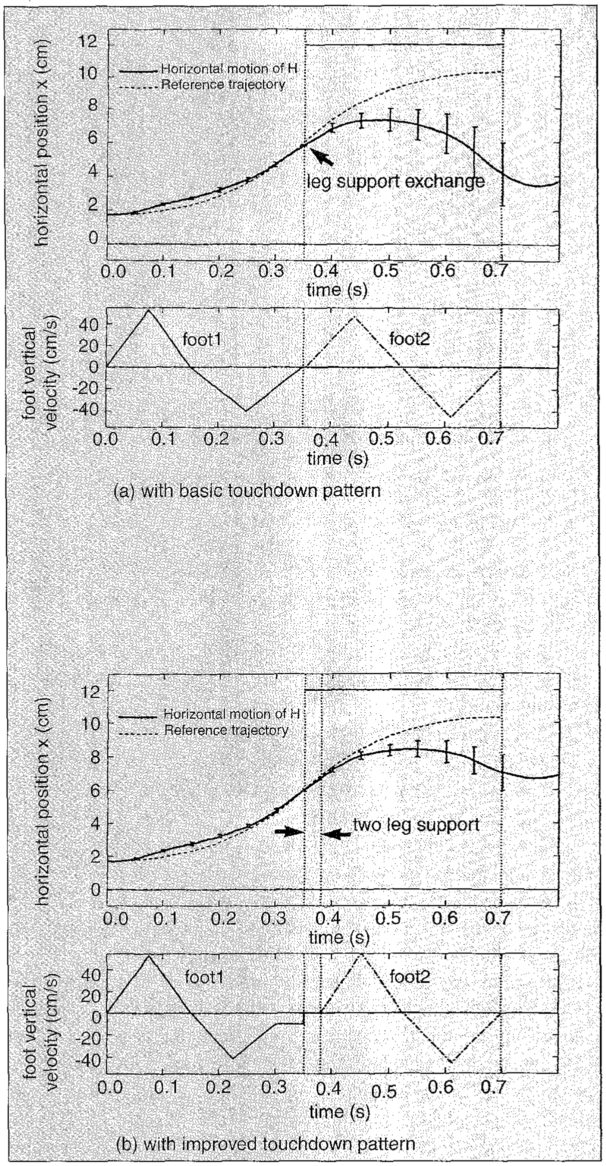

Fig. 8. Results of support exchange experiment (a) with basic touchdown pattern and (b) with improved touchdown pattern.

down with zero speed. In experiment (b), foot1 was controlled to hit the floor at a speed of 10cm/s.

We can explain the better result of experiment (b) as follows. In experiment (a), foot1 was slowed down near the floor and occasionally touched the floor prior to the expected time (0.35s) due to position error and disturbances. In experiment (b), on the other hand, foot1 had a specified speed and thus realized more punctual touchdown. Since the touchdown time determines the motion after the exchange, this punctual touchdown helped to realize a near-ideal motion even though the robot was slamming its feet into the ground.

There was another difference between the swing leg motions in these experiments. In experiment (a), foot2 was lifted up from the floor as soon as foot1 touched down, while in (b), foot2 was lifted 30ms after the touchdown of foot1 so that there was a two-leg support period of 30ms. The result shows that a two-leg support state helps to smooth the exchange of support, though it is very short (0.03s) compared with the step period (0.7s). One possible explanation for this result is as follows: due to the position error or disturbances, foot1 occasionally touches the floor later than the expected time. In such a case, when foot2 is lifted up immediately at 0.35s as in experiment (a), the body loses its balance and foot1 hits the floor at an unexpected high speed, which results in a large loss of momentum. In contrast, delayed lifting of foot2 as in experiment (b) can keep the body balance until the final touchdown of foot1 and helps a smooth exchange.

Walking Experiment

The walking control system consists of the support leg control and the swing leg control.

Fig. 9 shows the robot walking over a box of 3.5 cm height (strobe light 80 times/min). The step length was 12 cm and the step period was 0.6s. In this article we use the term "step length" to describe the distance between successive footholds and "step period" for the period between successive support leg exchange. The position and height of the box were measured and programmed before the experiment, and the robot started from a predefined position. The lines are the trajectories of the LEDs mounted on the hip joint and on the right ankle. We can see the trajectory of the hip joint which was controlled to be on the constraint line.

Fig. 10 shows the data of which the robot walked over a step of 2 cm height. The period of stepping up is indicated by an arrow. The upper graph shows the horizontal displacement of the feet with respect to the hip joint (thin line: right foot, thick line: left foot). The vertical lines at 0.1s, 0.4s, 1.0s, 1.6s, 2.2s, 2.8s, and 3.1s indicate the times of leg support exchange.

While a foot is supporting the body (i.e., on the ground), we can regard the data as meaning the body motion with respect to the ankle. For example, in the period from 0.1s to 0.4s, the thick line indicates the horizontal motion of the hip joint H with respect to the left ankle. Then, the robot exchanged leg support from the left to right leg at 0.4s. From 0.4s to 1.0s, the thin line indicates the body motion with respect to the right ankle. For each support phase, the reference trajectory (x_{ref}) is indicated by a broken line.

The lower graph of Fig. 10 indicates the ankle current (thin line: right ankle, thick line: left ankle). While a foot was in the

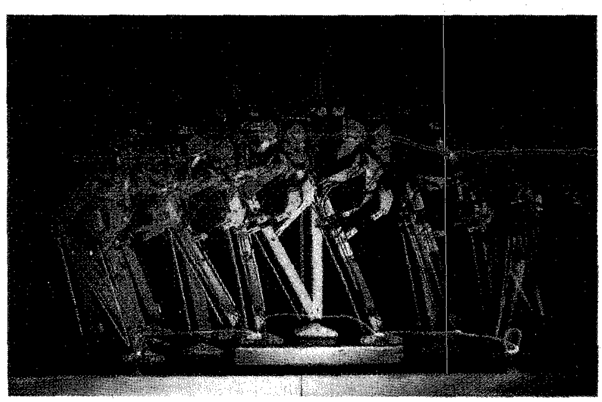

Fig. 9. Walking over a box (step length 12cm, step period 0.6s, box height 3.5cm).

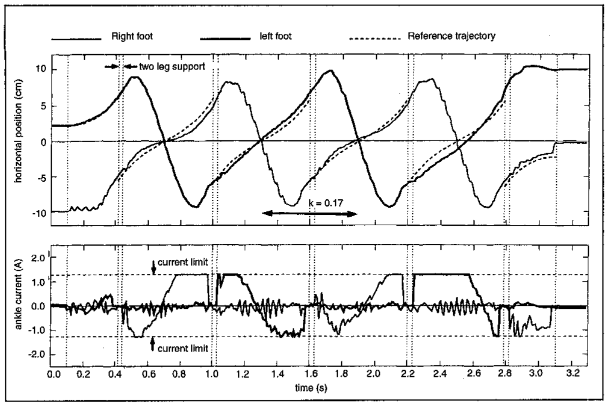

Fig. 10. Experimental data.

support phase, its ankle torque was used for the model following control (Equation (11)) and the ankle joint consumed a large amount of current. For example, the thin line from 0.4s to 1.0s and the thick line from 1.0s to 1.6s show the ankle torque used for the support phase control.

While a foot was in swing phase, it was controlled to keep it parallel to the ground surface. The ankle joint consumed a small amount of current for this control.

As discussed in "Model Following Control" (Equation (12)), the absolute ankle current (torque) was limited (the horizontal dashed line). First, we calculated the maximum ankle current (torque) using Equation (13). If the maximum current was too large, the robot could not keep the sole in contact with the floor during its support, and if the maximum current was too small, the model following control (Equation (11)) did not work. In either of these cases, the walking was not stable. By carrying out several walking experiments, we determined that successful walking was realized with a maximum ankle current of 1.3A.

These walking experiments have been reported by way of video proceedings [8].

Conclusions

In this article we developed a control system for a six-d.o.f. biped robot "Meltran II" using a "Linear Inverted Pendulum Mode" theory. We carried out two experiments to check effects not well discussed in the theory. The support phase experiment showed that the support phase dynamics can be regarded as linear though the legs, which were assumed to be massless in the theory, have mass. The support exchange experiment was performed to check leg support exchange. We found that a smooth leg support exchange is achieved by making the foot contact with a specified vertical speed and by holding two-leg support for a certain short period.

Based on these results, a whole biped control system was implemented. In our experiment, the robot successfully walked over a box of 3.5 cm height at a speed of 20 cm/s.

Currently, we are carrying out an experiment of real-time gait control in the linear inverted pendulum mode. Using an ultrasonic range sensor mounted on the body, the robot can walk over the ground of unknown profiles [7].

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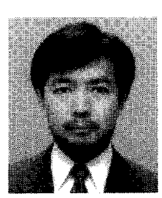

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