A BALANCE CONTROL IN BIPED DOUBLE SUPPORT PHASE BASED ON CENTER OF PRESSURE OF GROUND REACTION FORCES

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Abstract: The center of pressure (CoP) of ground reaction forces is an effective factor to evaluate the biped balance. From this point of view, we proposed a new CoP control method based on its feedback information. In this paper, we apply it to the weight shifts in the double support phase of the biped system. This method does not require the desired trajectories of joint angles, because of which the CoG is adaptively controlled according to the external forces without re-designing the motion pattern. The simulations and robot experiments will show the effectiveness of this control law.

Keywords: Biped system, ground reaction force, center of pressure, double support phase, stability

1. INTRODUCTION

The balance control is a fatal problem for the biped locomotion. The concept of ZMP (zero moment point) (Vukobratovic *et al.*, 1989) is proposed in order to design motion patterns such that keep balance during the locomotion, in other words, do not make foot rotations. In fact, many biped robots adopt a control strategy in that the desired trajectories of joint angles are firstly designed based on the ZMP condition and after that the feedback control is executed for the designed ones (Vukobratovic *et al.*, 1989; Takanishi *et al.*, 1988). However, in this strategy, the ZMP is controlled in a feed forward manner in a sense that the actual ZMP position is not measured by sensors and not used for torque determination, implying that it has a weakness for environmental variations or parameter errors: the motion patterns cannot be designed without assuming any environmental conditions and modeling parameters. If the actual environmental conditions are different from these assumptions, the ZMP is not controlled to the desired position even if the joint angles track exactly the designed trajectories. Recently, some papers reported methods in which the desired positional trajectories are modified according to the measured ZMP position (Hirai *et al.*, 1998; Haung *et al.*, 2000; Park and Cho, 2000). In these works, the robot behaviors are examined only experimentally, or sometimes by simulations, and thus the mathematical consideration is not sufficiently mentioned.

In order to cope with environmental variations such as a change of the ground gradient, it is effective to make use of the information on ground reaction forces. From this scope, we proposed a static balance control method for the biped upright posture in the previous paper (Ito *et al.*, 2001), where we achieved a adaptive posture changes according to external force by controlling the ground reaction forces (see the next section). The purpose of this paper is to extend this method to biped locomotion control. For the first step, we here consider the weight shift control during double support phase within the frontal plane, since this motion is fundamental for biped locomotion next to upright standing: From upright standing to walking motion, humans have to shift their weight to the one side in order to swing forward the leg in the other side. Our stance in this paper is that the desired trajectory of joint angles is not directly designed. Instead, we design the trajectory of the CoP of ground reaction

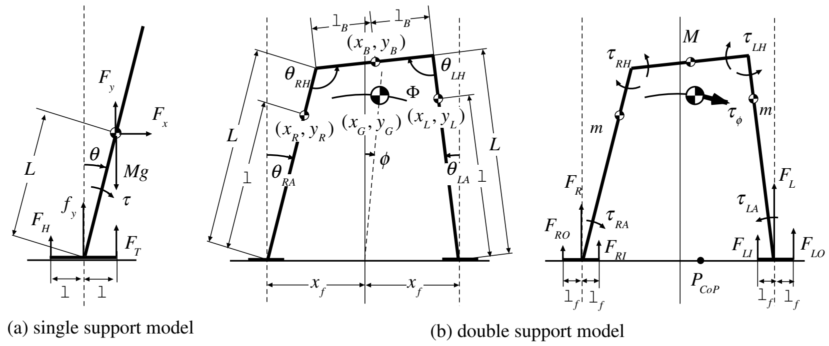

Fig. 1. Link model.

forces and so the motion pattern emerges as an indirect result of the CoP control. The CoP is known to be equivalent to ZMP (Goswami, 1999). Therefore, our method is regarded as the feedback control of ZMP. Owing to this feedback, even though the environmental conditions gradually change, the balance is maintained as before.

2. UPRIGHT POSTURE CONTROL BASED ON GROUND REACTION FORCES

Firstly, we review a balance control based on the ground reaction forces proposed in the previous paper (Ito *et al.*, 2001), since it forms the basis of our approach in this paper. Assumptions of the control law are follows. The biped system consists of body part and foot part, which are connected at the ankle joint as shown in Fig. 1(a). The motion occurs only in the sagittal plane. The ankle joint angle θ and its velocity $\dot{\theta}$ are detectable, while appropriate torque τ is actively generated at the ankle joint. The foot part contacts to the ground at the two points, i.e., heel and toe, where the vertical component of the ground reaction force there, i.e., F_H and F_T, are measurable. The foot part does not slip on the ground and its shape is symmetrical in the anterior-posterior direction. The ankle joint is located at the midpoint of the foot part with zero height.

Suppose here that unknown constant external force is exerted, whose horizontal and vertical component is F_x and F_y, respectively. If balance is kept, only the body part has dynamics which is described as the motion equation,

$$\begin{aligned} I\ddot{\theta} &= MLg\sin\theta + F_xL\cos\theta - F_yL\sin\theta + \tau. \\ &= AL\sin(\theta - \theta_f) + \tau \end{aligned} \tag{1}$$

where

$$A = \sqrt{(Mg - F_y)^2 + F_x^2} \tag{2}$$

and θ_f is a constant satisfying

$$\sin\theta_f = -\frac{F_x}{A}, \ \cos\theta_f = \frac{Mg - F_y}{A}. \tag{3}$$

And, M is mass of the body part, I is its moment of inertia around the ankle joint, L is the length between ankle joint and center of gravity (CoG) of the body part and g is the gravitational acceleration.

The goal of the control is to keep the postural balance regardless of the constant external force F_x and F_y. It is most effectively achieved by making F_T and F_H equal. As one solution of it, the following theorem is available.

Theorem: For the dynamical system (1), consider the torque input τ as follows:

$$\tau = -K_d\dot{\theta} + K_p(\theta_d - \theta) + K_f\int(F_H - F_T)dt. \tag{4}$$

If feedback gain K_d, K_p and K_f satisfy the conditions

$$K_p > AL > 0 \tag{5}$$

$$\frac{\ell}{I}K_d > K_f > 0 \tag{6}$$

$$(K_d\ell - K_fI)K_p > K_d\ell AL, \tag{7}$$

then, $F_H = F_T$ holds at the stationary state and $\theta = \theta_f$ becomes a local asymptotic stable posture.

Proof: Firstly, we define a new state variable τ_f by the following equation,

$$\tau_f = \int(F_H - F_T)dt. \tag{8}$$

Substituting (4), (1) turns to

$$\begin{aligned} I\ddot{\theta} = &AL\sin(\theta - \theta_f) \\ &-K_d\dot{\theta} + K_p(\theta_d - \theta) + K_f\tau_f, \end{aligned} \tag{9}$$

On the other hand, the ground reaction forces are described with ankle joint torque as,

$$F_T = -\frac{1}{2\ell}\tau + \frac{1}{2}mg + \frac{1}{2}f_y, \tag{10}$$

$$F_H = \frac{1}{2\ell}\tau + \frac{1}{2}mg + \frac{1}{2}f_y, \tag{11}$$

where m is a mass of the foot part and ℓ is the length from the ankle joint to the toe or the heel, and f_y is the vertical component of the force from the body part.

Differentiating (8) and then substituting (10), (11) and (4), we obtain

$$\dot{\tau}_f = \frac{1}{\ell}(-K_d\dot{\theta} + K_p(\theta_d - \theta) + K_f\tau_f). \quad (12)$$

The dynamical system described by (9) and (12) have an equilibrium point $(\bar{\theta}, \bar{\tau}_f)$,

$$(\bar{\theta}, \bar{\tau}_f) = (\theta_f, \frac{K_p}{K_f}(\theta_f - \theta_d)) \quad (13)$$

Note that $F_H = F_T$, because $\dot{\tau}_f = 0$ at the stationary state. By analyzing the stability of this equilibrium point with the linearized equations, (5)-(7) can be derived from Routh/Hurwitz method. □

3. CONTROL IN DOUBLE SUPPORT PHASE

3.1 Problem and assumptions

Here, we attempt to extend the method in the previous section to the weight shift control in the biped double support phase within the frontal plane. The problem is to move the point on which body's weight is placed into the desired position. Then, we use a model as shown in Fig. 1(b). This consists of 5 links containing one body part, two leg parts and two foot parts. Ankle joints are assumed to be located at the center of foot part with zero height. At both sides of foot part, the ground reaction forces are detectable. Furthermore, at the ankle and the hip joints, angular deviations its velocities are measurable as well as the joint torque are generated.

3.2 Control law

In the double support phase, the foot parts keep contact to the ground, which makes closed link mechanism. Although 3 links, i.e., body part and two leg parts, actually move, the degree of freedom (DoF) of this mechanism is only one. Because the control method in the previous section is also for 1-DoF motions, we utilize it for the problem here. However, there are three differences from the upright posture control in the previous section: Firstly, the contact points are more than two, i.e., four contact points. Second, the orbit of CoG motion is not an extact circle. Third, the torque generation is redundant. To solve problems originating from these differences, we modify the control law in the following sections.

3.2.1. Description using CoP The most serious problem is the difference in the number of the contact points. The difference between F_H and F_T is calculated in (4) as the number of contact points is only two. How should we do when the number of them increases to four?

Now, we introduce the concept of CoP. The CoP is a representative point when the ground reaction forces are assumed to act only at the single point. Around CoP, the moment generated by the vertical component of all the ground reaction forces become zero. Using this characteristic, the position of CoP in Fig. 1(a) can be calculated as follows,

$$P_{CoP} = \frac{F_T\ell - F_H\ell}{F_T + F_H}, \quad (14)$$

where, P_{CoP} is the position of CoP from the midpoint of the foot part. If the motion is slow, we can regard $F_T + F_H$ as constant, since it just represents the total mass. Thus, defining constant K_w as

$$K_w = \frac{\ell}{F_T + F_H}, \quad (15)$$

the above equation changes to

$$P_{CoP} = -K_w(F_H - F_T). \quad (16)$$

Using this relation, (4) can be written as

$$\begin{aligned}\tau = &-K_d\dot{\theta} + K_p(\theta_d - \theta) \\ &+ K_f' \int(P_d - P_{CoP})dt. \end{aligned} \quad (17)$$

which have been extended to control the position of CoP to its desired value P_d. Here, $K_f' = K_f/K_w$.

In the case of the double support phase, the position of CoP, P_{CoP}, is calculated from the vertical component of ground reaction forces at four contact points, i.e., F_{RO}, F_{RI}, F_{LO}, and F_{LI}, in the same way:

$$\begin{aligned}P_{CoP} = &-\frac{F_{RO}}{F_{all}}(x_f + \ell_f) - \frac{F_{RI}}{F_{all}}(x_f - \ell_f) \\ &+\frac{F_{LI}}{F_{all}}(x_f - \ell_f) + \frac{F_{LO}}{F_{all}}(x_f + \ell_f) \end{aligned} \quad (18)$$

$$F_{all} = F_{RO} + F_{RI} + F_{LI} + F_{LO}. \quad (19)$$

Here, the subscript $_{RO}$, $_{RI}$, $_{LI}$ and $_{LO}$ respectively represent the position of contact point, i.e., the right outside, the right inside, the left inside and the left outside, ℓ_f is the length from the ankle joint to the side of the foot part, and x_f is the distance to the ankle joint form the origin of the coordinates set at the midpoint of both ankle joints.

3.2.2. Coordinate frame for CoG motion In the biped upright model shown in Fig. 1 (a), the CoG of the body traces on the circular orbit. Therefore, if the angle of the circular orbit is selected as the generalized coordinate frame, the ankle joint torque can be defined as the generalized force. In the double support phase, however, the orbit of CoG in the frontal plane changes with the length between both feet, and thus does not always become circular. Thus, we have to arrange the definition of the coordinate frame on the orbit.

Here, the coordinate of CoG on this frame is presented by ϕ. It is preferable that this coordinate frame is naturally extended from the one for the single support phase. From this point of view, we define ϕ as the sway angle of CoG from the vertical direction.

$$\phi = \arctan \frac{x_G}{y_G}. \tag{20}$$

Here, (x_G, y_G) denotes the coordinate of CoG whose origin is set at the midpoint between both foot. Using the ankle joint angle in both side, i.e., θ_{RA} and θ_{LA}, the coordination of CoG can be described as

$$x_G = 2\rho \cos \frac{\theta_{RA} + \theta_{LA}}{2} \sin \frac{\theta_{RA} - \theta_{LA}}{2} \tag{21}$$

$$y_G = 2\rho \cos \frac{\theta_{RA} + \theta_{LA}}{2} \cos \frac{\theta_{RA} - \theta_{LA}}{2} \tag{22}$$

Here,

$$\rho = \frac{2m\ell + ML}{2(2m + M)}. \tag{23}$$

Using this relation, we obtain

$$\frac{x_G}{y_G} = \tan \frac{\theta_{RA} - \theta_{LA}}{2} \tag{24}$$

According to the definition of the generalized coordinate (20), ϕ is expressed as

$$\phi = \frac{\theta_{RA} - \theta_{LA}}{2}. \tag{25}$$

When the generalized force exerted in the tangential direction of the orbit by τ_ϕ, the control input is determined as

$$\begin{aligned} \tau_\phi = & -K_d \dot{\phi} + K_p(\phi_d - \phi) \\ & + K_f \int (P_d - P_{CoP}) dt \end{aligned} \tag{26}$$

Since this equation takes the same form as (4), the CoP is expected to converge to the desired value.

3.2.3. Joint torque calculation Next, we calculate the joint torque which produce the generalized force τ_ϕ. When CoG moves $\Delta\phi$ along the orbit, the hip and ankle joints also changes, the amount of which is put to $\Delta\boldsymbol{\theta}$ ($\boldsymbol{\theta} = [\theta_{RA}, \theta_{RH}, \theta_{LH}, \theta_{LA}]$). The subscript $_{RA}$, $_{RH}$, $_{LH}$ and $_{LA}$ represent the joint position, respectively, the right ankle, the right hip, the left hip and the left ankle. The relation between $\Delta\boldsymbol{\theta}$ and $\Delta\phi$ is described using the Jacobian matrix $\boldsymbol{J}(\boldsymbol{\theta})$ as

$$\Delta\boldsymbol{\theta} = \boldsymbol{J}(\boldsymbol{\theta})\Delta\phi. \tag{27}$$

In the coordinate frame deined in this section, the $\boldsymbol{J}(\boldsymbol{\theta})$ is calculated as follows. From (25)

$$\dot{\phi} = \frac{\dot{\theta}_{RA} - \dot{\theta}_{LA}}{2} \tag{28}$$

is satisfied. In addition, using the geometrical relation

$$-\theta_{RA} + \theta_{RH} + \theta_{LH} - \theta_{LA} = \pi \tag{29}$$

and constraint conditions of the parallel mechanism, the relation between $\dot{\boldsymbol{\theta}}$ and $\dot{\phi}$ becomes

$$\dot{\boldsymbol{\theta}} = \frac{2}{J_1 + J_3} \begin{bmatrix} J_1 \\ J_1 - J_2 \\ J_2 - J_3 \\ -J_3 \end{bmatrix} \dot{\phi} = \boldsymbol{J}(\boldsymbol{\theta})\dot{\phi} \tag{30}$$

$$J_1 = 2\ell_2 \sin \theta_{LH} \tag{31}$$

$$J_2 = \ell_2 \sin(\theta_{LH} + \theta_{RH}) \tag{32}$$

$$J_3 = 2\ell_2 \sin \theta_{RH}. \tag{33}$$

From the principle of virtual work, the next relation holds between the generalized force τ_ϕ and the joint torques $\boldsymbol{\tau} = [\tau_{RA}, \tau_{RH}, \tau_{LH}, \tau_{LA}]$,

$$\tau_\phi = \boldsymbol{J}^T(\boldsymbol{\theta})\boldsymbol{\tau} \tag{34}$$

Solving this equation, the joint torques are given by

$$\boldsymbol{\tau} = (\boldsymbol{J}^T(\boldsymbol{\theta}))^* \tau_\phi + (I - \boldsymbol{J}^T(\boldsymbol{\theta})(\boldsymbol{J}^T(\boldsymbol{\theta}))^*)\boldsymbol{p} \tag{35}$$

Here, $*$ denoted its generalized inverse matrix, and $\boldsymbol{p}$ is an arbitrary 4-dimensional vector.

3.3 Stationary state

In this section, we consider the stationary state which is achieved by the control law (26). Here, we assume that the joint angles can be described as a function of ϕ, i.e., $\boldsymbol{\theta} = \boldsymbol{\theta}(\phi)$, which is possible if $0 < \theta_{RH}, \theta_{LH} < \pi$. Note that the tangent line of CoG orbit is not generally vertical. We can describe the motion equation using ϕ as

$$M(\boldsymbol{\theta})\ddot{\phi} + C(\boldsymbol{\theta}, \dot{\boldsymbol{\theta}}) + G(\boldsymbol{\theta}, g, \boldsymbol{F}) = \tau_\phi. \tag{36}$$

where, G contains not only the gravity but also external force $\boldsymbol{F}$, i.e., F_x and F_y in (1). From the mechanical property, $M(\boldsymbol{\theta}) > 0$ and $C(\boldsymbol{\theta}, \dot{\boldsymbol{\theta}})$ become the second order term of $\dot{\theta}$. On the other hand, the joint torque gives effect to the CoP through τ_ϕ, whose relation is expressed as

$$P_{CoP} = P(\boldsymbol{\theta})\tau_\phi + Q(\boldsymbol{\theta}, \dot{\boldsymbol{\theta}}) + R(\boldsymbol{\theta}, g, \boldsymbol{F}) \tag{37}$$

Now, we have defined the control input τ_ϕ by (26). For the simplicity of calculation of stationary state, we here introduce a new state variable τ_f,

$$\tau_f = \int (P_{CoP} - P_d) dt \tag{38}$$

Then, the motion equation (36) for ϕ becomes

$$M(\boldsymbol{\theta})\ddot{\boldsymbol{\theta}} + C(\boldsymbol{\theta}, \dot{\boldsymbol{\theta}}) + G(\boldsymbol{\theta}, g, \boldsymbol{F}) = \\ -K_d\dot{\phi} + K_p(\phi_d - \phi) + K_f\tau_f. \quad (39)$$

On the other hand, differentiating τ_f, we can get

$$\dot{\tau}_f = P_{CoP} - P_d. \quad (40)$$

Substituting (37), the above equation becomes

$$\dot{\tau}_f = P(\boldsymbol{\theta})(-K_d\dot{\phi} + K_p(\phi_d - \phi) + K_f\tau_f) \\ +Q(\boldsymbol{\theta}, \dot{\boldsymbol{\theta}}) + R(\boldsymbol{\theta}, g, \boldsymbol{F}) - P_d \quad (41)$$

Regarding ϕ, $\dot{\phi}$, τ_f as state variables, we can obtain the stationary state $\bar{\phi}$, $\bar{\tau}$. Here, what is important is that $\dot{\tau}_f = 0$ at the stationary state, which implies that $P_{CoP} = P_d$.

3.4 *Stability*

For the stability analysis, we linearize (39) and (41) around the equilibrium point $(\bar{\phi}, \bar{\tau}_f)$:

$$\bar{M}\Delta\ddot{\phi} + \frac{\partial\bar{G}}{\partial\boldsymbol{\theta}}\bar{J}\Delta\phi = \Delta\tau_\phi \quad (42)$$

$$\Delta\dot{\tau}_f = -(\frac{\partial\bar{R}}{\partial\boldsymbol{\theta}} + \frac{\partial\bar{P}}{\partial\boldsymbol{\theta}}\bar{\tau}_\phi)\bar{J}\Delta\phi - \bar{P}\Delta\tau_\phi \quad (43)$$

Here, $\bar{M} = M(\bar{\boldsymbol{\theta}})$, $\bar{J} = J(\bar{\boldsymbol{\theta}})$, $\bar{P} = P(\bar{\boldsymbol{\theta}})$, $\frac{\partial\bar{G}}{\partial\boldsymbol{\theta}} = \frac{\partial G(\bar{\boldsymbol{\theta}})}{\partial\boldsymbol{\theta}}$, $\frac{\partial\bar{R}}{\partial\boldsymbol{\theta}} = \frac{\partial R(\bar{\boldsymbol{\theta}})}{\partial\boldsymbol{\theta}}$, $\frac{\partial\bar{P}}{\partial\boldsymbol{\theta}} = \frac{\partial P(\bar{\boldsymbol{\theta}})}{\partial\boldsymbol{\theta}}$. The controlability matrix of the above linear system is

$$\begin{bmatrix} 0 & \frac{1}{\bar{M}} & 0 \\ \frac{1}{\bar{M}} & 0 & -\frac{1}{\bar{M}^2}\frac{\partial\bar{G}}{\partial\boldsymbol{\theta}}\bar{J} \\ -\bar{P} & 0 & -\frac{1}{\bar{M}}\left[\frac{\partial\bar{R}}{\partial\boldsymbol{\theta}} + \frac{\partial\bar{P}}{\partial\boldsymbol{\theta}}\bar{\tau}_\phi\right]\bar{J} \end{bmatrix} \quad (44)$$

If this matrix is full rank, the stationary state becomes local stable for the suitable feedback gains K_p, K_d and K_f, which will be designed e.g., by using the solution of Ricatti equation for LQ theorem. Since $\bar{\tau}_\phi = K_p(\phi_d - \bar{\phi}) + K_f\bar{\tau}_f = \bar{G}$, the determinant of the controllability matrix becomes

$$\frac{1}{\bar{M}^3}\frac{\partial}{\partial\boldsymbol{\theta}}(\bar{P}\bar{G} + \bar{R})\bar{J} = \frac{1}{\bar{M}^3}\frac{\partial}{\partial\phi}(PG + R)\bigg|_{\phi=\bar{\phi}} \quad (45)$$

Here, we assume that (45) is zero. Substituting (36) into τ_ϕ of (37) and linearlize (37) around the equilibrium point, we obtain

$$\Delta P_{CoP} = PM\Delta\ddot{\phi} + \frac{\partial}{\partial\phi}(PG + R)\bigg|_{\phi=\bar{\phi}}\Delta\phi \quad (46)$$

When ϕ is deviated from $\bar{\phi}$ slowly, $\Delta\ddot{\phi}$ is regarded as zero. Then, $\Delta P_{CoP} = 0$, since we assume (45) is zero. It means that CoP stays at the same position if ϕ changes slowly. That will be possible if the CoG moves vertically. However, the tangent line of CoG orbit is not generally vertical. So, it contradicts and the controllability matrix should be full rank, implying that the linear system is a controllable.

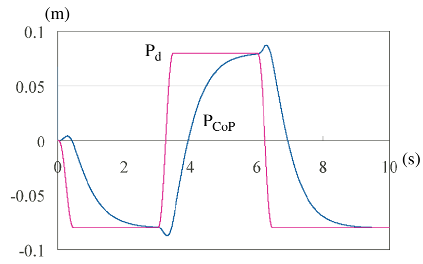

Fig. 2. CoP position for $F_x = 0$.

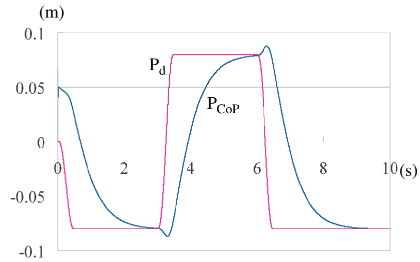

Fig. 3. CoP position for $F_x = 0.1Mg$.

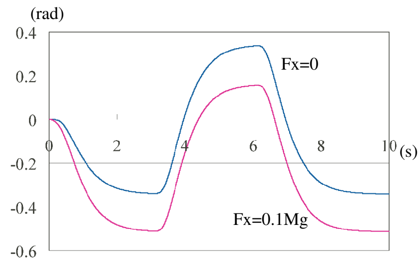

Fig. 4. Comparison of sway angle ϕ.

4. SIMULATION

Parameters and initial state are set as follows: $M = 2.5$, $m = 1.0$, $m_f = 0.25$, $L = 0.34$, $\ell = 0.17$, $\ell_B = 0.08$, $\ell_f = 0.03$ and, $\theta_{RA} = \theta_{LA} = 0.05$, $\theta_{RH} = \theta_{LH} = \frac{\pi}{2} + 0.05$. In this setting, the length between left and right foot is slightly larger than the one between two hip joints. The goal behavior is given so that the CoP is shifted to left side, right side, and again left side and kept to left side within 10 sec. The generalized force τ_ϕ is determined by (26), and next the joint torque, by (35) with taking the torque limitation of ankle joints into account. Two cases are tested: no external force and non-zero horizontal external force, i.e., $F_x = 0.1Mg$. The CoP position with its desired value are shown in Fig. 2 for the former case, whereas in Fig. 3 for the latter case. Regardless of the external force, the similar time evolutions are observed except the initial response. However, the difference is shown clearly in the time course of ϕ, which is illustrated in Fig. 4. In the case of

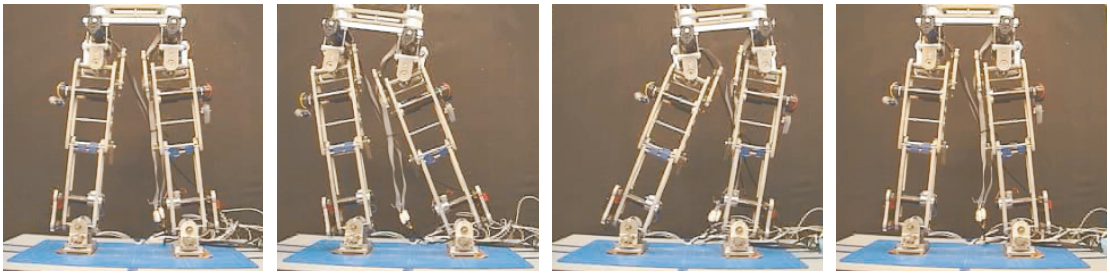

Fig. 5. robot behaviors in the experiment.

no external force, ϕ shows the symmetrical trajectory. However, when the external force works, the motion is biased to the direction against the external force, which implies that the body is inclined on the whole against it.

5. ROBOT EXPERIMENT

In order to examine the effectiveness of the control method, we execute the robot experiment. The behavior observed in the experiment is shown in Fig. 5. The robot consists of 7 links (body, two thighs, shanks and feet). The height from ground to the hip join is about 40 cm at the upright posture, the horizontal distance between hip joints is 16 cm, and the foot width is 6 cm for each side. The DoFs of the robot are 12 (3 in hip, 1 in knee and 2 in ankle for one leg). However, in order to restrict the motion in the frontal plane, the DoFs of the pitch and yaw rotation in the hip, knee, and ankle joints are mechanically locked respectively. Moreover, in order to place the weight evenly in the both side of the foot, i.e., to let $F_{RI} = F_{RO}$ and $F_{LI} = F_{LO}$, we set the ankle torque zero, which is achieved by making the ankle joints free. Consequently, only the hip joint torque in the roll axis controls the lateral motion in the frontal plain. The total weight of the robot is about 5.0 kgf. The angles of each joint are measured by rotary encoders installed in each motor, while the ground reaction forces are measured by the loadcells attached at each corner of the sole.

The initial posture is set so that the legs are slightly open, i.e., the distance between ankle joints becomes 24 cm. The desired and actual trajectory of CoP in the experiment on the horizontal floor is shown in Fig. 6. The CoP almost tracks the desired trajectory with slight delay. The similar results are also obtained from another experiment where the legs are set parallel each other in the initial state, which make the balance more difficult to maintain than from the previous condition.

6. CONCLUSION

In this paper, we consider the CoP control in the double support phase of biped system. We proposed a method using the feedback of the ground reaction forces, in which the CoP position becomes the main controlled variable. In this method, the desired trajectory of joint angle is unnecessary, since this control is essentially force control. Thanks to this characteristic, the behavior, i.e., the CoG trajectory automatically changes with the constant external force. As a feature works, we extend it to the stepping motion and finally the locomotion.

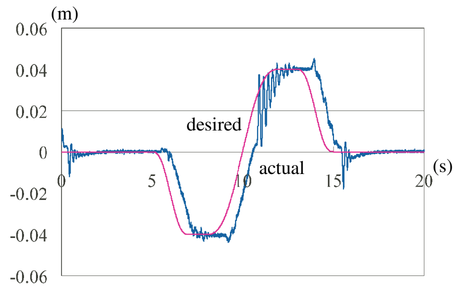

Fig. 6. CoP position of robot experiment in the level floor.

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