# Upright Posture Stabilization by Ground Reaction Force Control

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## Abstract

When standing on a slope, a human adjusts his or her posture, i.e., ankle joint angles adjust to the gradient of the slope. In such adaptive behavior, ground reaction forces play an important role. Based on this view, we propose a new posture control law that employs PD and force feedback control, and prove its effectiveness in creating local stability. Applying this control law to a simple robot system, we examine this law's efficiency. In this experiment, the robot achieves a behavior adaptive to constant external force. Finally, we discuss the possibility of control only using force feedback in consideration of human muscle properties.

**Key Words:** Posture control, Ground reaction force, Adaptation, External force, Stability

## 1 INTRODUCTION

To maintain upright posture is one of the noticeable characteristics of human motion. In such a simple but fundamental motion, humans select an adequate posture with respect to their environmental conditions. For example, when standing on a slope, a person adjusts his or her ankle joints in such a way that the body is always oriented in the gravitational direction. In a flow field, e.g., in a river or storm, a human leans his or her body upward against the flow. The control mechanism of such an adaptive behavior constitutes an area of significant interest, and should be elucidated in light of specific motor function. However, the formalization of changes in the adaptive standing posture,including environmental models, have been rarely reported.

Previous studies of balance control in a biped system have focused on ground reaction forces. This information is used for the measurement of actual ZMP (zero moment point) position [1, 2, 3], or an impedance control of a swinging leg especially at the point of touchdown [4]. However, few works have described systems that depend on ground reaction forces, i.e., have selected them for use as control variables.

In this paper, we focus on ground reaction force, since we also consider that the ground reaction forces include useful information to achieve an adaptive behavior in standing posture control. In the proposed control law in the present study, the forces (more precisely, the difference of forces at both ends of the foot) are treated as control variables. Generally, when controlling the force, the position is not controlled in this direction, which often make body balance unstable. Thus, in our previous work [5], we have reported another control law and its simulations, where two force control laws are switched alternatively. However, this method requires a high frequency of switching, and thus did not work well when applied to actual legged robot systems. Based on this result, we aimed at a method that did not require the switching. Here, we describe a new control method and analyze its stability, and show the result of its experimental application.

## 2 MODEL AND CONTROL

### Motion equation with environment

A human body has a complex structure with many links and joints. Among these joints, ankle joints exert the most crucial effect on human balance control, because the ankle joints are located at the base of human standing posture. A slight displacement of the ankle joint creates a large deviation in the COG (center of gravity) of the body. Of course, the displacements of the other joint angles also influence position, but these influences are relatively smaller than that of the ankle joint. Therefore, we assume that the displacement of joint angles other than that of the ankle is small during upright standing, and so represent the body part in terms of this single link.

The problem we should solve is how to determine the ankle joint torque which achieves adaptive posture adjustment to environmental conditions. In the present study, we consider the environmental force to be constant, as is the case when we stand on sloping surface or in a constant flow field (air flow or water flow).

In light of these problem settings, we modeled a standing legged system as shown in Fig. 1. This model consists of two links: a body part and a foot part. These two links are connected at the ankle joint, and torque for balance control can be generated here. For the sake of simplicity, the motion of this model is restricted to the sagittal plane on level ground. The model contacts the ground only at the two points of the foot, i.e., toe and heel. Here, the vertical component of ground reaction forces $F_T$ (at the toe) and $F_H$ (at the heel) are detectable by the force sensors.

Assuming that the friction on the ground is so large that the foot does not slip on it, only the body part is

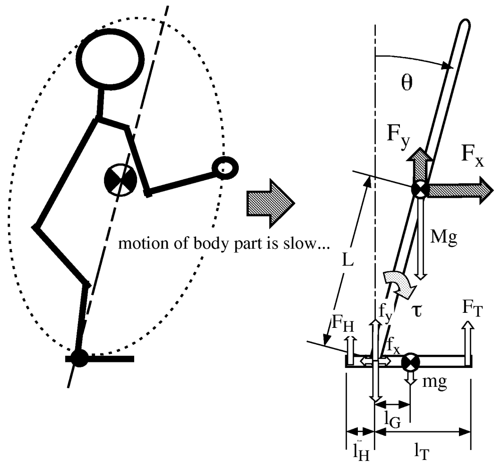



Figure 1: Link model.

dynamic and this motion is described as

$$I\ddot{\theta} = MLg\sin\theta + F_x L\cos\theta - F_y L\sin\theta + \tau, \qquad (1)$$

where $M$ is the mass of the body part, $I$ is the inertial moment of the body part around the ankle joint, $L$ is the length between ankle joint and the COG of the body part, $\theta$ is the ankle joint angle from the vertical direction, $\tau$ is the ankle joint torque, $F_x$ and $F_y$ are constant external forces, respectively, in the horizontal and vertical directions, and $g$ is gravitational acceleration. Note that the environment is represented by $F_x$ and $F_y$. Internal force between links, $f_x$ and $f_y$, is described as

$$f_x = ML\ddot{\theta}\cos\theta - ML\dot{\theta}^2\sin\theta - F_x, \qquad (2)$$

$$f_y = -ML\ddot{\theta}\sin\theta - ML\dot{\theta}^2\cos\theta + Mg - F_y. \qquad (3)$$

Furthermore, from the balance of torques around the heel and toe, the vertical component of ground reaction forces, $F_T$ and $F_H$, are described as

$$F_T = -\frac{1}{\ell_T + \ell_H}\tau + m_T g + \frac{\ell_H}{\ell_T + \ell_H} f_y, \qquad (4)$$

$$F_H = \frac{1}{\ell_T + \ell_H}\tau + m_H g + \frac{\ell_T}{\ell_T + \ell_H} f_y. \qquad (5)$$

Here, $\ell_T$, $\ell_H$, and $\ell_G$ represent the length from the ankle joint to, respectively, the toe, heel, and COG of the foot. $m_T$ and $m_H$ is a mass of the foot weighted respectively to the toe and heel, which is given by

$$m_T = \frac{\ell_H + \ell_G}{\ell_T + \ell_H} m, m_H = \frac{\ell_T - \ell_G}{\ell_T + \ell_H} m, \qquad (6)$$

where $m$ is the total mass of the foot.

For simplicity of calculation, we normalize the external forces $F_x$ and $F_y$ by the gravitational force of the body,

$$F_x = \alpha Mg, F_y = \beta' Mg. \qquad (7)$$

Then, the motion equation (1) can be described as

$$\begin{aligned} I\ddot{\theta} &= \alpha MLg\cos\theta + (1-\beta')MLg\sin\theta + \tau \\ &= MLg\sqrt{\alpha^2+\beta^2}\sin(\theta - \theta_f) + \tau, \end{aligned} \qquad (8)$$

where $\beta = 1 - \beta'$ and $\theta_f$ satisfies the following equations

$$\sin\theta_f = -\frac{\alpha}{\sqrt{\alpha^2+\beta^2}}, \ \cos\theta_f = \frac{\beta}{\sqrt{\alpha^2+\beta^2}}. \qquad (9)$$

Note that $\alpha$ and $\beta$ determine the environmental conditions.

### A control law

**Instability by force-only control:** Initially, we assume a simple symmetrical mechanical structure, i.e., $\ell_T = \ell_H = \ell$ and $\ell_G = 0$. In order to maintain body balance, it is necessary that both $F_T$ and $F_H$ are always positive. Moreover, when body mass is evenly weighted between the toe and heel, stability will be greatest. So, a control law which reduces the difference between $F_T$ and $F_H$ will be easily accessible. From (4) and (5), we obtain the relation between $F_H - F_T$ and $\tau$

$$F_H - F_T = \frac{1}{\ell}\tau. \qquad (10)$$

Thus, if we define the torque input as

$$\tau = -\ell \cdot K_I \int (F_H - F_T)dt, \qquad (11)$$

then $F_H - F_T$ goes to zero, and body mass is evenly weighted to both ends of the foot. Unfortunately, however, this torque input does not maintain an upright posture, since the body tumbles while maintaining $F_H - F_T = 0$. This will be shown in the next section.

**PD and force feedback control :** In order to stabilize the body parts, we firstly utilize the PD control laws:

$$\tau_\theta = -K_d\dot{\theta} + K_p(\theta_d - \theta). \qquad (12)$$

Here, $K_d$ and $K_p$ are positive constants corresponding to the velocity and position feedback gains, respectively. $\theta_d$ is the desired joint angles of the PD control, and should be zero when the object of control is to make the body upright. Due to the external forces, however, $\theta$ does not converge to $\theta_d$. Substituting $\tau = \tau_\theta$ to (8), we obtain the equation

$$I\ddot{\theta} = MLg\sqrt{\alpha^2+\beta^2}\sin(\theta-\theta_f) - K_d\dot{\theta} + K_p(\theta_d - \theta). \qquad (13)$$

Assuming that $\theta - \theta_f \sim 0$, we can linearize the above equation at $\theta = \theta_f$, and then get the following equation

$$\ddot{\theta} = -\frac{K_d}{I}\dot{\theta} - (\frac{K_p - MLg\sqrt{\alpha^2+\beta^2}}{I})(\theta - \theta_0), \qquad (14)$$

where

$$\theta_0 = \frac{K_p\theta_d - MLg\sqrt{\alpha^2+\beta^2}\theta_f}{K_p - MLg\sqrt{\alpha^2+\beta^2}}. \qquad (15)$$

This equation implies that $\theta$ converges to $\theta_0$ if $K_p > MLg\sqrt{\alpha^2+\beta^2}$.

At this stage, the balance of the body is maintained by the PD control. Next, we add to it the adaptation torque in relation to environmental changes. As mentioned in the Sec. 2, it is preferable for the sake of stability that the body weight is placed evenly on both ends of the foot. According to this criterion, we define force feedback input as

$$\tau_f = \int (F_H - F_T)dt, \tag{16}$$

and the resultant torque is constructed by the PD and Force feedback control (PDF control):

$$\tau = \tau_\theta + K_f \tau_f. \tag{17}$$

Here, $K_f$ is a force feedback gain. $K_f$ should be sufficiently smaller $K_p$ and $K_d$, because the adaptation occurs after the body balance is maintained completely by the PD control.

**Stability analysis:** For the PDF control input (17), we can ensure the local stability of the body part.

**Theorem 1** *For the dynamical system (1) with symmetrical structure $\ell_T = \ell_H = \ell$ and $\ell_G = 0$, consider the control input given by (12), (16), and (17). If the feedback gain $K_d$, $K_p$, and $K_f$ satisfies the inequalities,*

$$K_p > MLg\sqrt{\alpha^2+\beta^2} > 0 \tag{18}$$

$$\frac{\ell}{I}K_d > K_f > 0 \tag{19}$$

$$(K_d\ell - K_f I)K_p > K_d \ell MLg\sqrt{\alpha^2+\beta^2} \tag{20}$$

*then $\theta = \theta_f$ becomes the local asymptotic stable equilibrium point.*

**Proof 1** *Substituting (17) to the motion equation (1), we can obtain*

$$I\ddot{\theta} = MLg\sqrt{\alpha^2+\beta^2}\sin(\theta-\theta_f) - K_d\dot{\theta} + K_p(\theta_d-\theta) + K_f\tau_f. \tag{21}$$

*On the other hand, differentiating (16) and then using (10),*

$$\dot{\tau}_f = \frac{1}{\ell}(-K_d\dot{\theta} + K_p(\theta_d-\theta) + K_f\tau_f). \tag{22}$$

*Now, calculate an equilibrium point $(\bar{\theta}, \bar{\tau}_f)$ of the dynamics described by (21) and (22). By substituting $\ddot{\theta} = \dot{\theta} = 0$ and $\dot{\tau}_f = 0$, (21) and (22) respectively become,*

$$MLg\sqrt{\alpha^2+\beta^2}\sin(\theta-\theta_f) + K_p(\theta_d-\theta) + K_f\tau_f = 0, \tag{23}$$

$$\frac{1}{\ell}(K_p(\theta_d-\theta) + K_f\tau_f) = 0. \tag{24}$$

*Solving two algebraic equations, we obtain*

$$(\bar{\theta}, \bar{\tau}_f) = (\theta_f, \frac{K_p}{K_f}(\theta_f - \theta_d)). \tag{25}$$

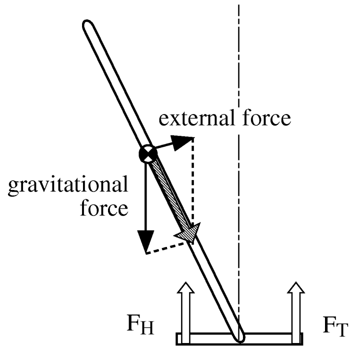



Figure 2: Stationary posture

*Next, let us examine the stability of this equilibrium point. Differential equations linearized at the equilibrium point are,*

$$\begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \\ \dot{\tau}_f \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ \frac{MLg\sqrt{\alpha^2+\beta^2}-K_p}{I} & -\frac{K_d}{I} & \frac{K_f}{I} \\ -\frac{K_p}{\ell} & -\frac{K_d}{\ell} & \frac{K_f}{\ell} \end{bmatrix} \begin{bmatrix} \theta_1 \\ \theta_2 \\ \tau_f \end{bmatrix}, \tag{26}$$

*where $\theta_1 = \theta$ and $\theta_2 = \dot{\theta}$. Thus, the characteristic equation are given by*

$$\lambda^3 + p_2\lambda^2 + p_1\lambda + p_0 = 0 \tag{27}$$

*where*

$$p_2 = \frac{K_d\ell - K_f I}{I\ell}, p_1 = \frac{K_p - MLg\sqrt{\alpha^2+\beta^2}}{I}$$
$$p_0 = \frac{K_f MLg\sqrt{\alpha^2+\beta^2}}{I\ell}. \tag{28}$$

*According to the method described by Routh/Hurwitz, the necessary and sufficient conditions that the equilibrium point becomes stable are given as*

$$p_0 > 0,\ p_1 > 0,\ p_2 > 0,\ p_1p_2 - p_0 > 0 \tag{29}$$

*From these inequalities, we can derive the conditions (18)-(20).*

It should be noted that the control input (11) does not satisfy conditions (18)-(20) since $K_d = K_p = 0$. Therefore, a control law with force-only feedback (11) does not maintain body balance.

**Control for asymmetrical structure:** In this section, we extend the control input (17) for the case that $\ell_H \neq \ell_G$ and $\ell_G \neq 0$. Then, $F_T$ and $F_T$ are not always equal even though the body stands upright under a non-perturbed environment, i.e., $F_x = F_y = 0$. This is because the mass weights are applied to the toe and heel unevenly due to the asymmetrical structure. Taking this into account, we design the adaptation torque $\tau_f$ as

$$\tau_f = \int (F_H - F_T - (m_H - m_T)g - \frac{\ell_T - \ell_H}{\ell_T + \ell_H}\bar{f}_y)dt \tag{30}$$

where $\bar{f}_y$ can be obtained from (4) and (5),

$$\bar{f}_y = F_H + F_T - (m_T + m_H)g. \quad (31)$$

Using (30) as the force feedback input, we can ensure the stability of the body part in the same way.

**Theorem 2** *For the dynamical system (1), let $\ell = \frac{\ell_T + \ell_H}{2}$ and consider the control input given by (17) with (12) and (30). If the feedback gain $K_d$, $K_p$, and $K_f$ satisfies the inequalities (18) - (20), then $\theta = \theta_f$ becomes the local asymptotic stable equilibrium point.*

**Stationary posture**

In the stationary state, ankle joint angle $\theta$ converges to $\theta_f$ when using the torque input (17). This stationary posture is not determined until the environmental conditions $\alpha$ and $\beta$ are given. At this posture, the moment of gravitational force and external force around the ankle joint are balanced. In short, the body part is oriented to the direction of the resultant force of the two, as shown in Fig. 2. For example, the body stands upright if no external forces are exerted. This posture has the advantage of requiring only a small amount of torque to maintain it, and so is more efficient from the energetic point of view.

Analyzing the stability of control law (17), we linearized the nonlinear motion equation. Thus, the condition $\theta \sim \theta_f$ is required. This condition implies that the external force does not suddenly change in an impulsive manner. We can estimate, using (18), the magnitude of the acceptable impulsive external force. This indicates that the posture can adapt to large changes of external force, if the change is slow enough to consistently satisfy (18),

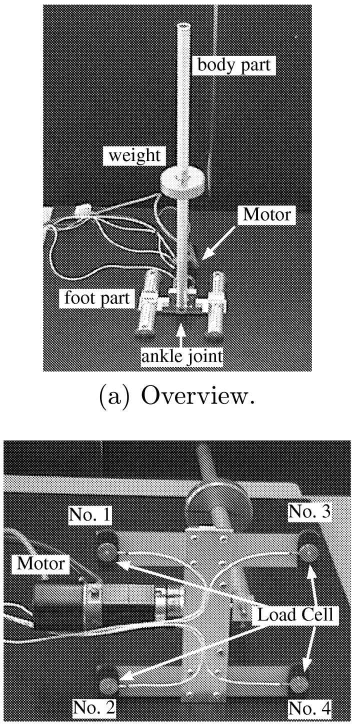
## 3 EXPERIMENTS

**Setup**

We design a simple robot for the experiments. This robot consists of a body part and foot part, as modeled in Fig. 1. The body is $0.55(m)$ height and the foot length is $0.12(m)$. It possesses a DC motor at the ankle joint, which moves the body part within the saggital plane. The ankle joint angle is detected by the encoder built in the motor. In addition, four small loadcells are attached on the corner of the sole, as shown in Fig. 3(b). The ground reaction forces $F_T$ or $F_H$ are computed by adding the sensor output from loadcell No. 1 and No. 3, or No. 2 and No. 4. To adjust the position of the COG, a $0.42(kg)$ weight is put at the middle of the body part. The total weight of the robot becomes about $1.11(kg)$.

**Results**

We firstly put the robot on the horizontal plate. We, then, lifted one side of the plate by hand in order to make and maintain a slope. After about 10(s), we returned back the plate to be the horizontal position.




(a) Overview.

(b) Four loadcells on the sole.

Figure 3: A designed robot

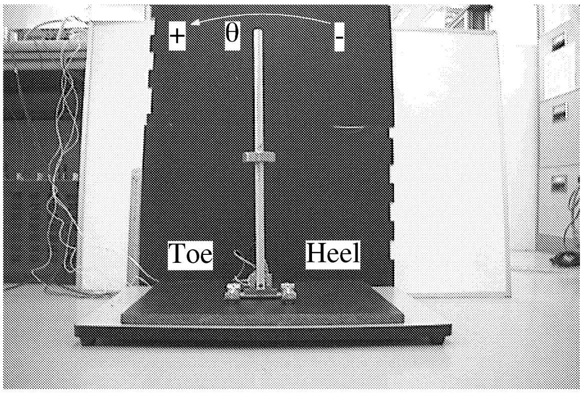
The torque input was computed every $1(ms)$ based on the ankle joint angle as well as on the ground reaction forces by using (17). The feedback gain was set as $K_p = 2.5$, $K_d = 1.5$, and $K_f = 0.01$.

The postures at several stages are shown in Fig. 4. As shown, the posture was adjusted adaptively according to the slope angle. Figure 5 illustrates the data regarding this experiment. The change in an ankle joint angle is depicted in Fig. 5(a). When the plate was tilted, the ankle joint was settled at approximately $0.3(rad)$. On the other hand, it was near $0(rad)$ after the plate was re-leveled. Figure 5(b) shows the controller outputs $\tau$, $\tau_\theta$, and $K_f\tau_f$. While the slope ankle was maintained, the controller outputed a nonzero value (see the graph of $\tau$ around 10(s)) owing to the friction of reduction gears. However, it will go to zero if slope is maintained for enough longer time. The changes of ground reaction force $F_T$ and $F_H$ are shown in Fig. 5(c). This indicates that the posture was adjusted so that the difference of the ground reaction force becomes small.

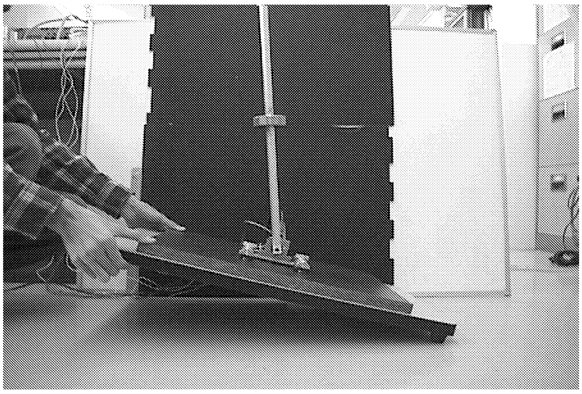
## 4 DISCUSSION

**Formalization in muscle system**

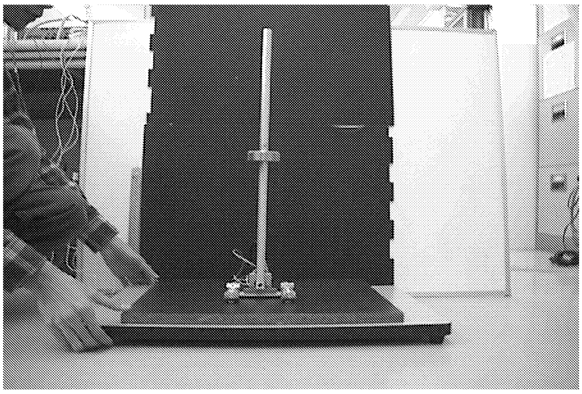
Using a PD and force feedback control, we can not only stabilize a body part, but also realize adaptive posture adjustment with respect to a specific environment, i.e., constant external force. In this, position/velocity feed-




(a) At the start.

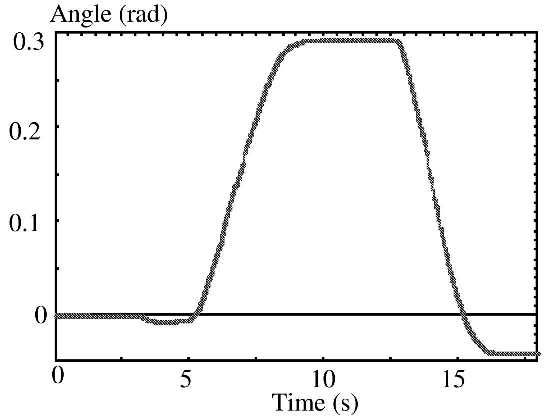


(b) On the tilted plate.

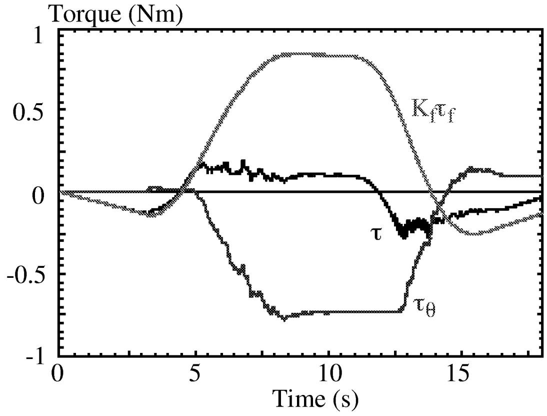


(c) At the final.

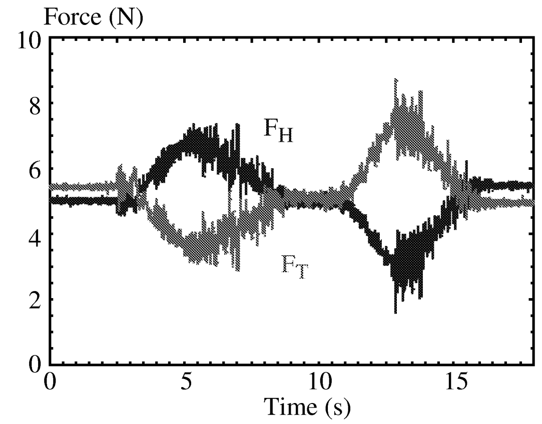
Figure 4: Posture changes by slope angle.




(a) Ankle joint angle $\theta$.




(b) Output of controller.




(c) Ground reaction force $F_T$ and $F_H$.

Figure 5: Experimental result

back is essential for stabilization, as mentioned in Sec. 2. However, the torque generated by PD control, $\tau_\theta$ in (12), can be replaced mechanically by spring and damper. Such a mechanical system does not need expensive sensors, such as encoders or tachometers. Fortunately, a stable posture $\theta = \theta_f$ does not depend on an equilibrium point of the spring $\theta_0$, which implies that we can set up the spring without rigid equilibrium point adjustment. In this way, it is quite possible to construct a posture control law using only force feedback.

In the case of human posture control, muscles play the roles of not only actuators but also springs and dampers. It is well-known that muscles have the elastic and viscous properties which increase with muscle activity. A bilinear muscle model represents this property well [6]. Using this model, the force generated by flexor $F_f$ and extensor $F_e$ are described as

$$F_f = u_f - ku_f x_f - bu_f \dot{x}_f, \tag{32}$$

$$F_e = u_e - k u_e x_e - b u_e \dot{x}_e. \tag{33}$$

Here, $u_f$ and $u_e$ denote muscle activities, and $x_f$ and $x_e$ are displacements from natural muscle length. The flexor and extensor are distinguished by the subscripts $f$ and $e$. Elasticity and viscosity, which are assumed to be the same in both muscles, are in proportional to the muscle activities with the positive constants $k$ and $b$, respectively. Put the moment arm of flexor and extensor to the same value, i.e., $\ell_m$, the muscle displacement is denoted approximately by

$$x_f = \ell_m \cdot \theta, \; x_e = -\ell_m \cdot \theta, \tag{34}$$

and the muscle torque becomes,

$$\begin{aligned} \tau_m &= \ell_m \cdot (F_f - F_e) \qquad (35) \\ &= \ell_m \cdot \{u_f - u_e - (u_f + u_e)(K\theta + B\dot{\theta})\}, \end{aligned}$$

where $K = k\ell_m$ and $B = b\ell_m$. It should be noted that (35) is described as the same form as (17).

To determine the joint torque $\tau_m$, we have to specify the activities of flexor and extensor, $u_f$ and $u_e$. Using force feedback, the difference $u_f - u_e$ should be determined as

$$u_f - u_e = \frac{K_f}{\ell_m} \tau_f. \tag{36}$$

On the other hand, the elasticity and viscosity of the ankle joint, can be adjusted by the addition $u_f + u_e$ so that (18) - (20) hold. Such muscle activities satisfying these two constraints ensure the stability of the posture control. This implies that, because of the elasticity and viscosity of muscles, PDF control can be achieved based on only force feedback information. Actually, we might observe where the weight is placed on the feet and make adjustments in this point of view, rather than place the ankle joint angles in its desired position, (i.e., the position feedback).

**Application to multi-link structure**

This control law indicates a method of determining the torque of the ankle joint based only on the local feedback of the ankle joint angle and ground reaction forces. This is equivalent to the ZMP control including external force. Usually, the concept of ZMP is utilized in motion planning of body parts in order to maintain the contact between the sole and floor [3]. Some studies have measured the actual ZMP using force sensors [1], and controlled it in a desired position [2]. However, the resultant movement of ZMP has not been clarified mathematically. In this paper, we show the local stability of the control law and its final posture theoretically, although it is in the realm of static balance control.

This control law is also applicable to standing posture control in a multi-link system on condition that changes in the link angles slowly alter the entire body posture. Then, the body part in Fig. 1 is regarded as a shank, and external forces are regarded as the force from the upper parts of the system, i.e., the thigh, trunk, arms and so on. In this case, we should newly take torque from the upper part into consideration. However, we can deduce the similar analytical result as that shown in Sec. 2.

## 5 CONCLUSION

In this paper, we considered human adaptive behavior as it regards standing posture control. Focusing on the ground reaction force, we proposed a new control law based on PD and force feedback control. We next discussed the possibility of a posture controller that uses only force feedback, and considered a human control mechanism in regard to the elastic and viscous properties of muscles. We performed robot experiment whose positive results indicated the controller's great applicability to the control system of a legged device.

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