# An Energy Consumption Based Control for Humanoid Walking*

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## Abstract

*This paper presents a framework of the energy consumption based control system for humanoid walking. Unlike the existing two approaches (one is based on precise control and powerful actuators (full control and wide applicability), and the other is passive dynamic walk (no control, therefore limited applicability)), the method aims at less energy consumption with more applicability. Knee stretching posture contributed to the former in general and a search algorithm based on the computer simulation enabled to find a feasible control to the given task.*

## 1 Introduction

Stable biped walking generally requires highly precise control and powerful actuator systems [1]; therefore its applicability seems broad. In these conventional biped walking algorithms, knees are always bended so that the walking can be stable; therefore, motors are highly loaded continuously. However, such a posture is quite different from normal human walking one. It should be noted that most of the existing control methods for humanoid walking are designed independent of the structural properties of the robot hardware.

On the other hand, the most energy efficient walking is passive dynamic walking (PDW) without any torque control [2]. In such methods, walking motions are determined by the relationship between a gravity potential effect and the parameters of the robot mechanical structure; therefore its realization is very sensitive to their parameters. Asano et al. realized the virtual PDW on a horizontal floor with a torque which generates a virtual gravity effect[3]. In these method, no control of walking behaviors such as dynamic change in step size or speed is possible as its name stands for.

Between above these two approaches, we aim at establishing the design principle for humanoid walking with less energy consumption than the full control system and more applicability than PDW.

If a robot walks without any task except for walking, it should walk with minimum energy consumption, else, that is, a robot walks with some tasks, it should change its walking motion faster and/or wider step size with consuming some extra energy. Ono et al. regarded biped locomotion as the combined motion of an inverted pendulum (supporting leg) and a 2 DOF pendulum (swing leg). As a result, they achieved human-like planar biped walking using simple self-excitation control[4]. Though this control method is similar to our approach, it has not focused on the energy consumption.

In this paper, we introduce a framework of the control system from a view point of less energy consumption, and verify its validity in the computer simulation.

## 2 Control Scheme

### 2.1 Kinematic Model

A cycle of bi-ped walking can be sub-divided into two phases; (1) one-leg supporting phase with controlling torque, and (2) landing phase without controlling torque (see Figure 1).

The basic idea behind the low-energy walking method is to consider one-leg supporting phase, as a combination of an inverted pendulum model (the supporting leg) and a 2 DOF normal pendulum one (the swing one). The inverted pendulum model is regarded as the most energy-efficient model as the

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*This work was partially supported by Kitano Symbiotic Systems Project, ERATO, JST

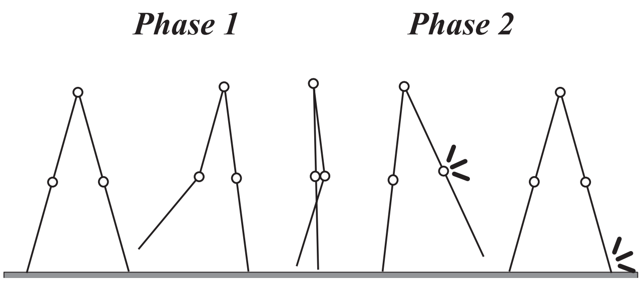

Figure 1: *The motion phases of one cycle*

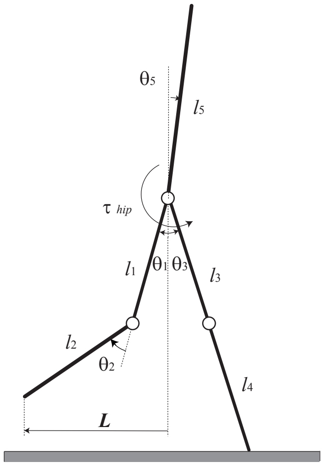

Figure 2: *Planar five-link model of the robot*

supporting leg in general.

Figure 2 shows a model we used in the experiment which consists of the five-link model with torso, and Table 1 shows parameters of all links. $\theta_i$ $(i = 1, ..., 5)$ denote the absolute joint angle of link $i$. We assume that every joint has a viscosity coefficient of 0.01 [N·m·s/rad], and that the knee joint also has a knee stopper. Each link has uniformly distributed mass $m_i$ $(i = 1, ..., 5)$, respectively.

### 2.2 Leg Control Scheme

In the full control, the walking control scheme generates the explicit walking pattern. The swing leg, for example, moves forward by the control torque.

Table 1: *Link parameters of a model*

| | | | | | |
|---|---|---|---|---|---|
| $m_1$ | [ kg ] | 0.400 | $l_1$ | [ m ] | 0.200 |
| $m_2$ | [ kg ] | 0.400 | $l_2$ | [ m ] | 0.200 |
| $m_3$ | [ kg ] | 0.400 | $l_3$ | [ m ] | 0.200 |
| $m_4$ | [ kg ] | 0.400 | $l_4$ | [ m ] | 0.200 |
| $m_5$ | [ kg ] | 0.900 | $l_5$ | [ m ] | 0.400 |

Therefore, we adopt the control method as follows:

$$\tau_{leg} = \begin{cases} -k_{leg}L & (0 \leq L) \\ 0 & (L < 0), \end{cases} \tag{1}$$

where $L$, $k_{leg}$, and $\tau_{leg}$ denote the horizontal distance between the hip joint and foot tip position, feedback gain, and feedback torque at the hip joint, respectively.

In the first phase shown in Figure 1, when $L$ is positive $(0 \leq L)$, the feedback torque $\tau_{leg}$ is added at the hip joint. This feedback torque makes the swing leg bend at the knee joint and swing forward without any other torque.

When $L$ is negative $(L < 0)$ (second phase), the feedback torque is not added to the hip joint. The swing leg moves forward freely until the swing leg locked at the knee joint, then it collides with the ground. The supporting and swing legs exchange immediately after the foot collision with the ground.

Adding torque at the hip joint can be regarded as adding torque at the tip of toe of the supporting leg because working point of the torque can be shifted an arbitrary point [5]. This control torque is, therefore, a driving force of its body explicitly.

The $k_{leg}$ is defined as

$$k_{leg(t+1)} = k_{leg(t)} + k_{ctrl}(E_d - E_{(t)}) + kv_{ctrl}\dot{E}_{(t)}, \tag{2}$$

where $E_d$, $E_{(t)}$, $k_{ctrl}$, and $kv_{ctrl}$ are desired energy consumption, energy consumption on $T = t$, and feedback gains, respectively.

An energy consumption is calculated as,

$$E_{(t)} = \sum_i \int \tau_i \dot{\theta}_i dt, \tag{3}$$

where $\tau_i$ and $\dot{\theta}_i$ denote the torque and angular velocity of the $i$-th $(i = 1, ..., 5)$ joint, respectively.

If we define the desired energy consumption $E_d$ and it is larger than current energy consumption $E_{(t)}$ which is calculated by Eq. 3, $k_{leg}$ at the next step increases by the Eq. 2.

Else $(E_d < E_{(t)})$, $k_{leg}$ at the next step decreases by the Eq. 2.

Finally, if the $E_{(t)}$ converges to $E_d$, a robot generates the continuous walking motion with desired energy consumption.

### 2.3 Body Control Scheme

In order to keep a upper body balance, the control represented in Eq. 4 is added between the upper body and the supporting leg,

$$\tau_{body} = k_{body}(\theta_{d5} - \theta_5) - kv_{body}\dot{\theta}_i, \tag{4}$$

where $k_{body}$ and $kv_{body}$ are the control gains, and $\theta_{d5}$ denotes the desired angle of $\theta_i$.

Table 2: *Control parameters of the simulation*

| | |
|---|---|
| $k_{ctrl}$ | 1.5 |
| $kv_{ctrl}$ | 0.2 |
| $k_{body}$ | 5.0 |
| $kv_{body}$ | 0.1 |
| $k_{leg}$ | 6.5 (Initial) |
| $kv_{leg}$ | 0.1 |

## 3 Dynamic Simulator

Dynamic simulations are realized by the fourth Runge - Kutta method, and the time interval is 0.2 [ms]. The dynamic equation of this model can be represented as follows:

$$[M(\theta)]\left\{\ddot{\theta}\right\} + [C(\theta)]\left\{\dot{\theta}^2\right\} + [K(\theta)] = [\tau], \qquad (5)$$

where $[M(\theta)]$, $[C(\theta)]$, and $[K(\theta)]$ denote the mechanical structure in terms of joint angles, and $[\tau]$ denotes feedback torque vector. In the computer simulations, the floor reaction force is calculated based on the spring - dumper contact model.

## 4 Condition

### (a) Control Gain

The simulation is performed with the parameters shown in Table 2. The initial gain parameter $k_{leg}$ is set as 6.5, and this gain is updated by Eq. 2 during the simulation. Another gain parameters $k_{ctrl}$, $kv_{ctrl}$, $k_{body}$, $kv_{body}$, and $kv_{leg}$ are fixed (constant).

### (b) Desired Energy Consumption

Every trial starts from the initial parameter set, in which the desired energy consumption $E_d$ is 0.4 [J]. A robot changes its control gain $k_{leg}$ by Eq. 2 during walking. If a robot can walk for 50 steps without falling over, the desired energy consumption is subtracted 0.02 [J] from current one until a robot falls over.

### (c) Body Swaying

Following six kinds of desired tilting forward angles of a body $\theta_{d5}$ are performed: 1.5, 2.0, 3.0, 4.0, 5.0, and 6.0 [deg]. If a trial is finished by the falling over of a robot, another $\theta_{d5}$ is examined.

Under the above conditions (a) - (c), we acquired pairs of the step size and step period in terms of each desired energy consumption $E_d$ and tilting forward angle of a robot $\theta_{d5}$ as shown in Table. 3.

Table 3: *Combination of desired energy consumption and tilting forward angle of a body*

| $E_d$ [J] | $\theta_{d5}$ [deg] | | | | | |
|---|---|---|---|---|---|---|
| 0.40 | 1.5 | 2.0 | 3.0 | 4.0 | 5.0 | 6.0 |
| 0.38 | 1.5 | 2.0 | 3.0 | 4.0 | 5.0 | 6.0 |
| 0.36 | 1.5 | 2.0 | 3.0 | 4.0 | 5.0 | 6.0 |
| 0.34 | 1.5 | 2.0 | 3.0 | 4.0 | 5.0 | 6.0 |
| 0.32 | 1.5 | 2.0 | 3.0 | 4.0 | 5.0 | 6.0 |
| 0.30 | 1.5 | 2.0 | 3.0 | 4.0 | 5.0 | - |
| 0.28 | 1.5 | 2.0 | 3.0 | 4.0 | - | - |
| 0.26 | 1.5 | 2.0 | 3.0 | - | - | - |
| 0.24 | 1.5 | 2.0 | - | - | - | - |
| 0.22 | 1.5 | 2.0 | - | - | - | - |
| 0.20 | - | 2.0 | - | - | - | - |

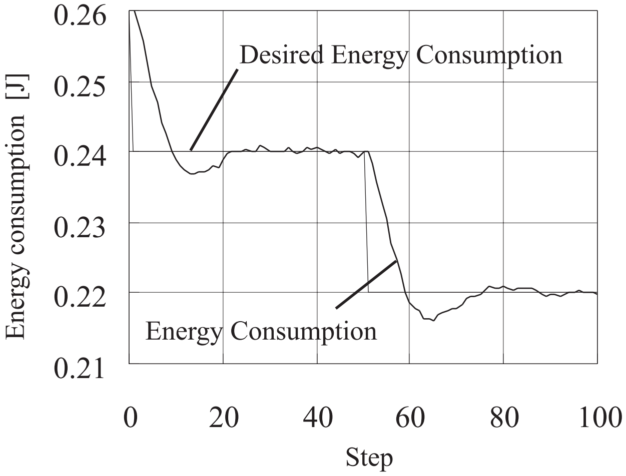

Figure 3: *Responce of energy consumption (at $\theta_2 = 2.0$ [deg])*

## 5 Experimental Results

### 5.1 Response of Energy Consumption

At first, the response of the energy consumption $E_{(t)}$ against the desired energy consumption $E_d$ is shown in Figure 3, when the energy consumption converges within 20 steps via transient period. After that, this system achieves a stable walking. We can see these tendencies in the all cases. Therefore, it is verified that this control system is valid for controlling energy consumption.

### 5.2 Effect of the step size and step period on energy consumption

The relationships between step size and energy consumption and between step period and energy consumption are shown in Figures 4 and 5.

From these two figures, we can see a robot can change

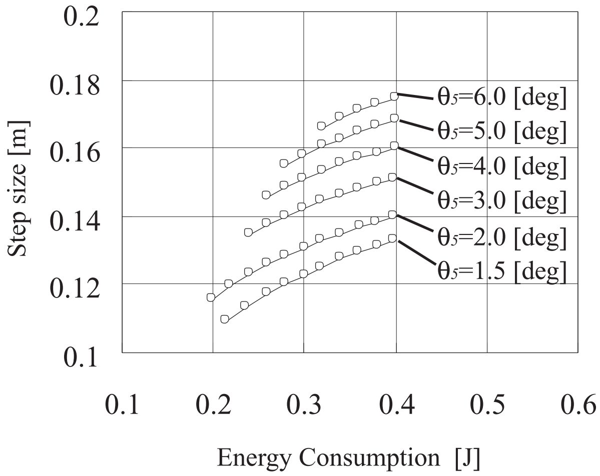

Figure 4: *Relationship between step size and energy consumption*

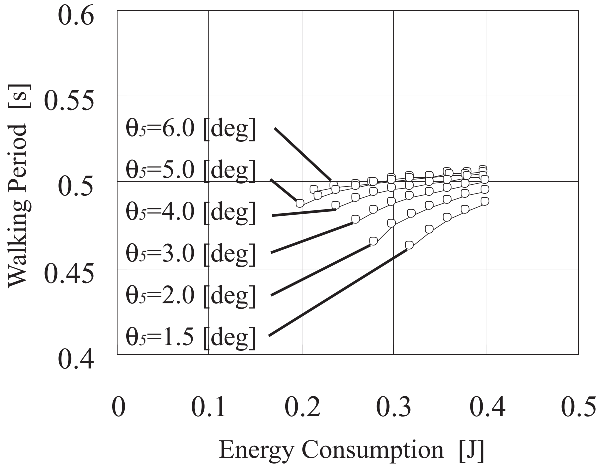

Figure 5: *Relationship between step period and energy consumption*

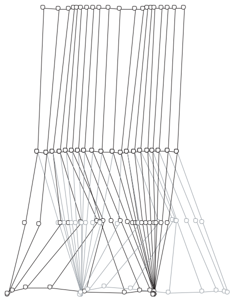

Figure 6: *($E_d$, $\theta_{d5}$) = (0.20, 2.0)*

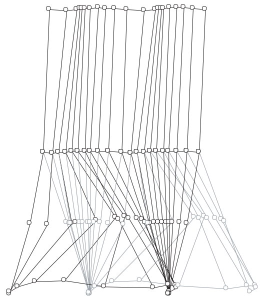

Figure 7: *($E_d$, $\theta_{d5}$) = (0.40, 2.0)*

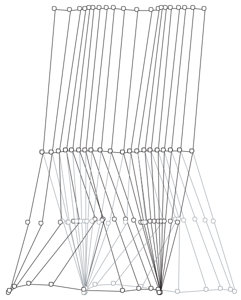

Figure 8: *($E_d$, $\theta_{d5}$) = (0.26, 4.0)*

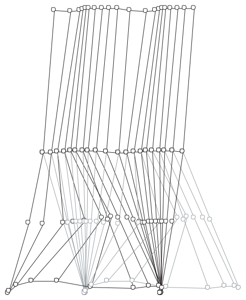

Figure 9: *($E_d$, $\theta_{d5}$) = (0.40, 4.0)*

the step size from 0.15 [m] to 0.17[m]. Also it can change the step period from 0.46 [sec] to 0.51 [sec].

### 5.3 Foot and Body Trajectories

Also, trajectories of one step walking in

$(E_d,\ \theta_{d5}) = (0.20,\ 2.0)$,
$(0.40,\ 2.0)$,
$(0.26,\ 4.0)$,
$(0.40,\ 4.0)$

are shown in Figures 6,7,8 and 9.

## 6 Discussion

### Effect of Body Swaying on Walking Speed

Relationship between an energy consumption and a walking speed of each tilting forward angle of a robot is shown in Figure 10, from which we can see that the tilting forward of a robot enables a robot to walk faster. Therefore if one likes to make the robot walk faster, the robot should bend its upper body forward.

### Effect of Energy Consumption on Walking Speed

In this model, a robot realize a walking speed from 0.23 [m/s] to 0.36 [m/s]. In order to realize such

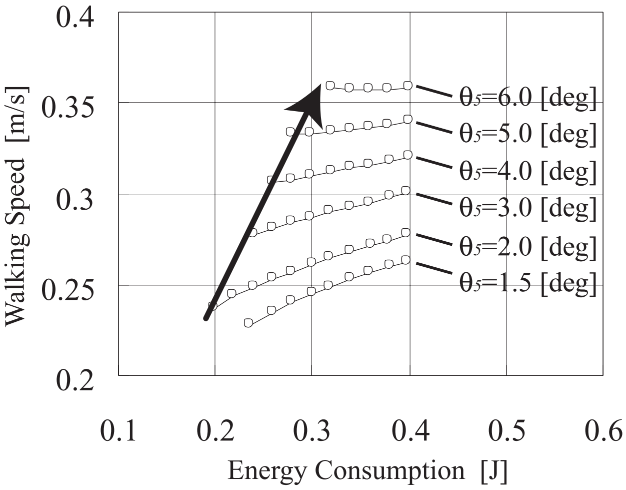

Figure 10: *Effect of body swaying on walking speed*

a walking speed, an energy consumption is required from 0.2 [J] to 0.32 [J].

If we make a robot walk with minimum energy consumption, we can set the desired energy consumption $E_d$ and tilting forward angle of a robot $\theta_{d5}$ along a bold arrow shown in Figure 10.

## 7 Conclusion and Future Work

In this paper, we introduce the framework of the energy consumption based control system for humanoid walking. We change the leg control gain $k_{leg}$ from the relationship between the desired energy consumption $E_d$ and current energy consumption $E_{(t)}$. As a result, it is verified that this control system enables a robot to walk with arbitrary energy consumption.

A current system, however, can not find a minimum energy consumption. In the future work, we have to find the minimum energy consumption in advance which can realize the walking motion without falling over in a variety of conditions, and implement this control method to a real robot.

### Acknowledgments

The dynamic simulator is supported by Mr. Masaki Ogino of Osaka University. The authors acknowledge him and members of the Asada Laboratory of graduate school of engineering, Osaka University, and members of Kitano Symbiotic Systems Project, ERATO, JST. Also, this research was partially supported by the Japan Science and Technology Corporation, in Research for the Core Research for the Evolutional Science and Technology Program (CREST) titled Robot Brain Project in the research area "Creating a brain."

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