A Control Method for Humanoid Biped Walking with Limited Torque

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Abstract. This paper presents an energy-efficient biped walking method that has been implemented in a low-cost humanoid platform, PINO, for various research purposes. For biped walking robots with low torque actuators, a control method that enables biped walking with low torque is one of the most important problems. While many humanoids use high-performance motor systems to attain stable walking, such motor systems tend to be very expensive. Motors that are affordable for many researchers have only limited torque and accuracy. Development of a method that allows biped walking using low-cost components would have a major impact on the research community as well as industry. From the view point of high energy-efficiency, many researchers have studied a simple planar walker without any control torque. Their walking motions, however, are decided by the relationship between a gravity potential effect and structural parameters of their robots. Thus, there is no control of walking behaviors such as speed and dynamic change in step size. In this paper, we propose a control method using the moment of inertia of the swing leg at the hip joint, and confirm that a robot controlled by this method can change its walking speed when the moment of inertia of the swing leg at the hip joint is changed without changing the step length. Finally, we apply this control method to the PINO model with torso in computational simulations, and confirm that the method enables stable walking with limited torque.

1 Introduction

The RoboCup Humanoid League [1], which is scheduled to start in 2002, is one of the most attractive research targets. We believe that the success of the humanoid league is critical for the future of RoboCup, and will have major implications in robotics research and industry. Thus, PINO[2][3] has been developed as a humanoid platform that can be widely used for many RoboCup researchers in the world. Figure 1 shows the whole view and the mechanical architecture of PINO.

In this paper, we present a first step toward energy-efficient biped walking methods that can be attained through low-cost, off-the-shelf components. At

(a) Whole view (b) Mechanism

Fig. 1. Picture and mechanism of PINO

the same time, energy-efficient walking may reflect actual human biped walking. Stable biped walking generally requires highly precise control and powerful actuator systems. It forces the use of expensive actuators and gear systems, so the total cost of the robot is very high. Due to the cost constraints, the motors that we can afford to use tend to have limited torque. Thus, we cannot apply conventional control methods of biped walking to PINO because of limited torque. It should be noted that most of the current control methods for humanoid walking are designed independent of the structural properties of the robot hardware. In general, these control methods require extremely large torque to realize desired walking patterns. The use of structural properties of a mechanical platform may significantly reduce the need for high torque motors by attaining energy-efficient behavioral patterns. Actuators can realize various kinds of behavior.

Recently, many researchers have reported studies on biped walking[4][5][6]. McGeer, especially, has studied PDW (Passive Dynamic Walk), in which simplest walkers can walk down a gentle slope without any actuators for controlling them[7], their walking motions are decided by the relationship between gravity potential effect and their structural parameters. Asano et al. realized the virtual PDW on a horizontal floor with a torque which generates a virtual gravity effect[8]. These control methods for PDW make much use of the structural properties to achieve highly energy-efficient walking. However, passive dynamic walkers cannot change their walking motions by themselves, thus such a control method is not adequate for humanoid walking for flexible of walking patterns.

On the other hand, Ono et al. regarded biped locomotion as the combined motion of an inverted pendulum and a 2 DOF pendulum. As a result, they achieved human-like planar biped walking using simple self-excitation control[9][10].

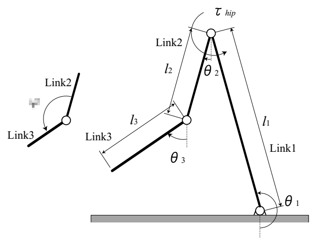

Fig. 2. Planar three link model of the robot

In the biped walking method, we started from the hypothesis that the walker can change the walking speed without changing the step length, if the moment of inertia of the swing leg at the hip joint has changed. Then, we proposed a simple control method based on our hypothesis, and confirmed that this control method is valid for biped walking on a planar model. Finally, we applied this control method to a planar four-link model with torso, and showed that appropriate swings of the torso enable the robot to walk with lower energy consumption. Through this study, we aim to achieve stable walking for PINO.

2 The Three-link Model

2.1 The Model

We consider the legs of PINO as a combination of an inverted pendulum model and a 2 DOF pendulum model, assuming the structure of PINO to be a planar walker. In this case, the inverted pendulum represents the supporting leg and the 2 DOF pendulum represents the swing leg. The inverted pendulum model is the most energy-efficient model at the supporting leg. Figure 2 shows the planar three-link model of the robot we assume. This model consists of link1, link2 and link3, and every link is connected in series. Link1 has a joint with the ground. Link1 and link2 are connected by the hip joint, and link2 and link3 are connected by the knee joint. 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. We define every joint angle θ_1, θ_2 and θ_3 as the absolute angle of link1, link2 and link3 respectively. Also, φ represents the angle between link2 and link3. Each link has uniformly distributed mass m_1, m_2 and m_3, respectively.

2.2 The Control Method

It is desirable that the control method is represented simply by structural properties. In this study, we choose the control method with the property of moment of inertia on the hip joint I_{hip} in order to verify our hypothesis. The moment of inertia of the swing leg on the hip joint I_{hip} can be represented as follows,

$$I_{hip} = \frac{1}{3}m_2 l_2^2 + \frac{1}{12}m_3 l_3^2 + m_3(x'^2 + y'^2) \tag{1}$$

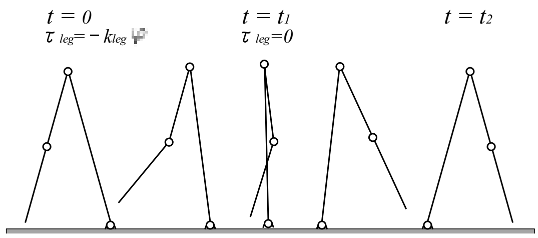

Fig. 3. The motion phases of one cycle

where x' and y' denote the center of gravity position of link3 as follows.

$$x' = l_2 sin\theta_2 + \frac{1}{2} l_3 sin\theta_3$$
$$y' = l_2 cos\theta_2 + \frac{1}{2} l_3 cos\theta_3 \quad (2)$$

From Eq. 1 and 2, φ can be represented as follows using I_{hip},

$$\varphi = f(Arccos(I_{hip})) \quad (3)$$

From Eq. 3, we define the control method as $k_{leg}\varphi$. Here, k_{leg} denotes the feedback gain. Also, we assume the walking motion consists of two phases as shown in Fig. 3.

In the first phase ($0 \le t \le t_1$), the feedback torque τ_{leg} is added at the hip joint. This feedback torque τ_{leg} makes the swing leg bend at the knee joint and swing forward without other torque. From the relationship between τ_{leg} and the time until the swing leg touches the ground t_2, the time to cut off the torque t_1 is decided. In the second phase ($t_1 < t \le t_2$), the feedback torque τ_{leg} does not add to the hip joint. The swing leg moves forward freely until it collides with the ground. Equation 4 shows the feedback torque at the hip joint.

$$\tau_{leg} = \begin{cases} -k_{leg}\varphi \ (0 \le t \le t_1) \\ 0 \qquad\quad (t_1 < t \le t_2) \end{cases} \quad (4)$$

where t_1 and t_2 are decided uniquely satisfying the law of conservation of angular momentum between immediately before and after foot collision as shown in Eq. 5.

$$[I(\theta)^-] \left\{\dot{\theta}^-\right\} = [I(\theta)^+] \left\{\dot{\theta}^+\right\} \quad (5)$$

where $[I(\theta)^-]$ and $[I(\theta)^+]$ denote inertia matrices. Also $\left\{\dot{\theta}^-\right\}$ and $\left\{\dot{\theta}^+\right\}$ denote the angular velocity vectors of immediately before and after foot collision. We assume that the collision between the swing leg and the ground, and the collision caused by the knee lock are perfectly non-elastic collisions. From Eq. 5, the final angular velocities of each link of one step are decided uniquely when we define the initial angular velocities of each link.

Also, the dynamic equation of this three-link model can be represented as,

$$[M(\theta)] \left\{\ddot{\theta}\right\} + [C(\theta)] \left\{\dot{\theta}^2\right\} + [K(\theta)] = [\tau] \quad (6)$$

Table 1. Link parameters

m_1	[kg]	1.500	l_1	[m]	0.5000
m_2	[kg]	0.750	l_2	[m]	0.2500
m_3	[kg]	0.750	l_3	[m]	0.2500

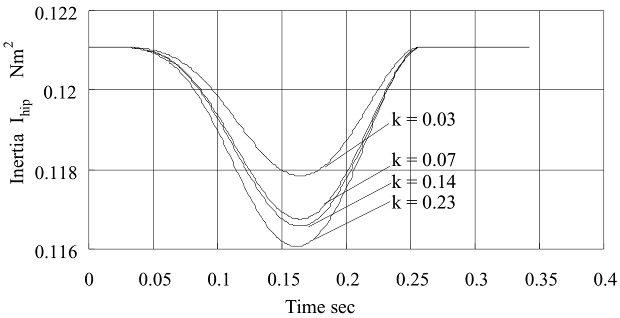

Fig. 4. Time series of I_{hip}

where $[M(\theta)]$, $[C(\theta)]$ and $[K(\theta)]$ denotes the parameter matrices of the mechanism and angular positions of the links, and $[\tau]$ denote feedback torque vector. Feedback torque vector $[\tau]$ can be represented as,

$$[\tau] = \left\{ -\tau_{hip}, \tau_{hip}, 0 \right\}^T \tag{7}$$

2.3 Verification of Effect of the Control Method on Three-link Model

We conducted preliminary computational simulations to verify that this control method is valid for the biped walking.

First, we define the link parameters of the robot as given in Table 1. We set the initial angular velocity $\dot{\theta}_i$ and we conduct computational simulations to change the feedback gain k_{leg} in order to change φ.

As a result, we obtain time series data of the inertia I_{hip} of the swing leg at the hip joint shown in Fig. 4. From the comparison of I_{hip} in each k_{leg}, we can use the minimum moment of inertia I_{min} as a performance index of I_{hip}. Figure 5 shows the effect of k_{leg} on t_2, and Fig. 6 shows the effect of k_{leg} on minimum moment of inertia I_{min} during walking. From these graphs, it is clear that the increase of k_{leg} causes a linear reduction of t_2 and I_{min}.

The time series of torque values of every k_{leg} and clearance to the ground of every k_{leg} are shown in Figs. 7 and 8 respectively. The maximum torque that we obtain from every k_{leg} ranges from 0.05 [N·m] (at $k_{leg} = 0.03$) to 0.35 [N·m] (at $k_{leg} = 0.23$). Considering this two-link swing leg model as a pendulum model consisting of a mass (M = 1.5 [kg]) and a link (L = 0.2795 [m]), the desired torque for swinging this pendulum is approximately 4.11 [N·m]. This control method, therefore, required the torque below one tenth than this torque, and

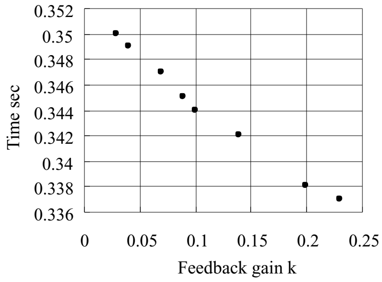

Fig. 5. Effect of k_{leg} on t_2

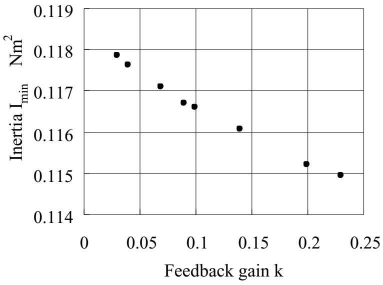

Fig. 6. Effect of k_{leg} on I_{min}

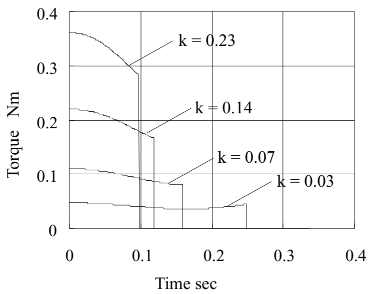

Fig. 7. Time series of torque value

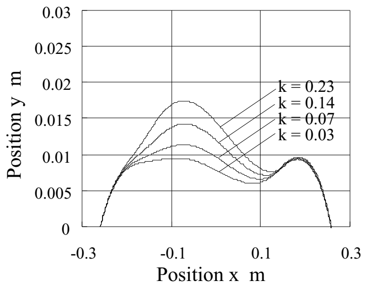

Fig. 8. Clearance to the ground

Table 2. Link parameters

m_1	[kg]	0.718	l_1	[m]	0.2785
m_2	[kg]	0.274	l_2	[m]	0.1060
m_3	[kg]	0.444	l_3	[m]	0.1725

it is clear that it can achieve the walking motion with high energy-efficiency. From Fig. 8, the clearance of the swing leg to the ground becomes larger as k_{leg} increases.

From the relationship among k_{leg}, t_2 and I_{min}, we can obtain the relationship between I_{min} and t_2.

From Fig. 9, it is clear that the reducing I_{min} causes fast walking, and increasing I_{min} causes slow walking. According to this relationship, we confirmed our hypothesis that the walker can change the walking speed when we change the moment of inertia of the swing leg at the hip joint, and this control method is valid for biped walking.

3 The Lower Limb Model of PINO

We apply this control method to the lower limb model of PINO. First, we define the link parameters of the robot as given in Table 2. We set the initial angular

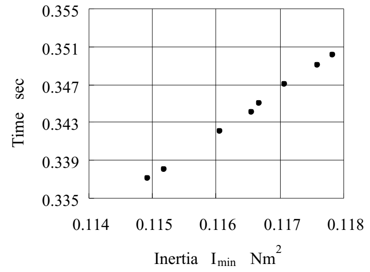

Fig. 9. Relationship between I_{min} and t_2

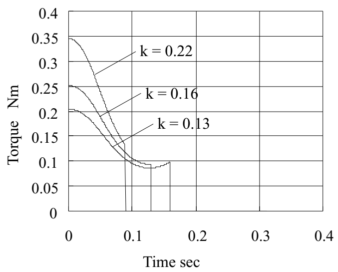

Fig. 10. Time series of torque value

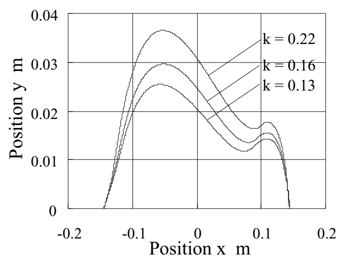

Fig. 11. Clearance to the ground

velocity $\dot{\theta}_i$ and conduct computational simulations to change the feedback gain k_{leg} in order to change φ.

As a result, we obtain the time series of torque values of every k_{leg} and clearance to the ground of every k_{leg} as shown in Figs. 10 and 11.

The maximum torque that we obtain from every k_{leg} ranges from 0.2 [N·m] (at $k_{leg} = 0.13$) to 0.35 [N·m] (at $k_{leg} = 0.22$). Considering this two-link swing leg model as a pendulum model consisting of a mass (M = 0.718 [kg]) and a link (L = 0.155 [m]), the desired torque for swinging this pendulum is approximately 1.09 [N·m]. This control method, therefore, required the torque below one third than this torque, and it is clear that it can achieve the walking motion with high energy-efficiency at lower limb model of PINO, too. From Fig. 11, the clearance of the swing leg to the ground becomes larger as k_{leg} increases. The maximum clearance of the swing leg to the ground ranges from 0.025 [m] (at $k_{leg} = 0.13$) to 0.035 [m] (at $k_{leg} = 0.22$). The minimum clearance ranges from 0.012 [m] (at $k_{leg} = 0.13$) to 0.017 [m] (at $k_{leg} = 0.22$).

4 Application to the Four-link Model with Torso

4.1 The Model and Control Method

We have verified that our proposed control method of the swing leg is valid for biped walking. Thus, as an application of the three-link model, we apply this

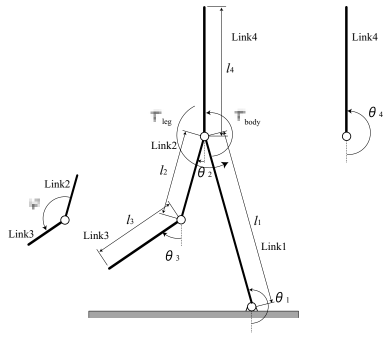

Fig. 12. Planar four-link model of the robot

Table 3. Link parameters

m_1	[kg]	0.718	l_1	[m]	0.2785
m_2	[kg]	0.274	l_2	[m]	0.1060
m_3	[kg]	0.444	l_3	[m]	0.1725
m_4	[kg]	3.100	l_4	[m]	0.4515

control method to the four-link model with torso, and verify the influence of the torso on the biped walking motion. Figure 12 shows the four-link model with torso. This model consists of link1, link2, link3 and link4, and link1 has a joint with the ground. We define every joint angle θ_1, θ_2, θ_3 and θ_4 as an absolute angle of link1, link2, link3 and link4 respectively. Each link has uniformly distributed mass m_1, m_2, m_3 and m_4, respectively. Table 3 shows the link parameters of the four-link model. We define the control method for the torso as $-k_{body}\theta_4$. Here, k_{body} denotes the feedback gain. We examined the effect of the feedback gain k_{body} on the walking motion. Feedback torque vector $[\tau]$ can be represented as follows,

$$[\tau] = \left\{ -\tau_{leg} + \tau_{body},\, \tau_{leg},\, 0,\, -\tau_{body} \right\}^T \tag{8}$$

4.2 Results and Discussion of the Model

We examine the three cases of the torso posture.

Case 1: We set the body feedback gain as $k_{body} = 14.0$, and the four-link model with torso moves using τ_{leg} and τ_{body}.

Case 2: We fix the torso vertically, and the four-link model with torso moves using only τ_{leg}.

Case 3: We examine the three-link model without torso to compare the three-link model without torso and the four-link mode with torso.

Also, we define the leg feedback gain as $k_{leg} = 0.5$ in every case in order to verify the effect of the torso on the biped walking motions.

Figures 13, 14 and 15 show the foot trajectory of every case. Table 4 shows the initial angular velocity $\dot{\theta}_1$, $\dot{\theta}_2$, $\dot{\theta}_3$, $\dot{\theta}_4$, time to touch down t_2 and energy consumption. From Table 4, t_2 of the four-link model with torso is longer than

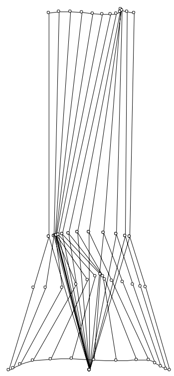

Fig. 13. Result of the foot gait of case 1

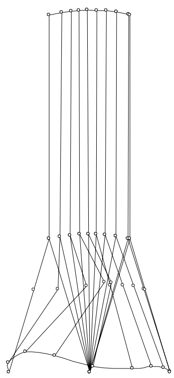

Fig. 14. Result of the foot gait of case 2

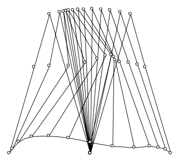

Fig. 15. Result of the foot gait of case 3

Table 4. Results of every case

Value		Case 1	Case 2	Case 3
$\dot{\theta}_1$	[rad/sec]	1.736	0.962	3.374
$\dot{\theta}_2$	[rad/sec]	1.692	0.223	1.384
$\dot{\theta}_3$	[rad/sec]	0.000	0.000	0.000
$\dot{\theta}_4$	[rad/sec]	1.309	—	—
t_2	[sec]	0.319	0.406	0.296
Energy consumption	[J]	0.064	0.109	0.025

that of the three-link model without torso t_2, and energy consumption of case 1 is smaller than that of case 2 though every angular speed is larger. From these results, it is verified that the walking motion with appropriate swings of the torso enables the robot to walk with lower energy consumption.

5 Conclusion

In this paper, we presented a method for energy-efficient biped walking, and applied the method to PINO, a low-cost humanoid robot. The proposed method aims to achieve stable biped walking with limited torque, so that it can be applied to humanoids that are built from low-cost, off-the-shelf components.

The conventional control method can not be used for such a robot, because it does not have sufficient torque to accommodate conventional control. Instead of using the conventional control method, we proposed and verified an energy-efficient biped walking method that exploits the structural properties of the mechanical platform. In this paper, therefore, we proposed a simple control method which is highly energy-efficiency using the structural properties. We chose the moment of inertia of the swing leg at the hip joint, and we applied feedback torque $\tau_{leg} = -k_{leg}\varphi$ to the hip joint.

As a result, in the lower limb model of PINO, the maximum torque required was reduced to the range of approximately 0.2 [N·m] (at $k = 0.13$) to 0.35 [N·m] (at $k = 0.22$), and it was confirmed that this enables the low-cost humanoid PINO to perform reasonably stable biped walking.

Also, the maximum clearance of the swing leg to the ground was adjusted to the range of approximately 0.025 [m] (at $k = 0.13$) to 0.035 [m] (at $k = 0.22$), and the minimum clearance to 0.012 [m] (at $k = 0.13$) to 0.017 [m] (at $k = 0.22$) which are sufficient for humanoid walking on a flat floor. Further, in the four-link model with torso, it was verified that appropriate swings of the torso enable the robot to walk with lower energy consumption low as 0.064 [J]. In the future, we intend to expand this control method to 3D space, and to apply this control method to the real humanoid PINO.

6 Acknowledgments

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