Mechanical Design Considering The Control Method for Humanoid Walking

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Abstract

We have proposed a highly energy-efficient control method for humanoid walking. The proposed control method enables a robot to walk with high energy efficiency using dynamics of the robot. In this case, however, the configuration of the robot hardware is decided by the mechanical designer. Most of these configurations are designed independently of the control method for walking. This paper, therefore, describes the optimal ratio between the upper limb and the lower limb of a robot from the view point of energy consumption. As a result, we obtain the optimal length ratio between upper limb and lower limb as 1.5.

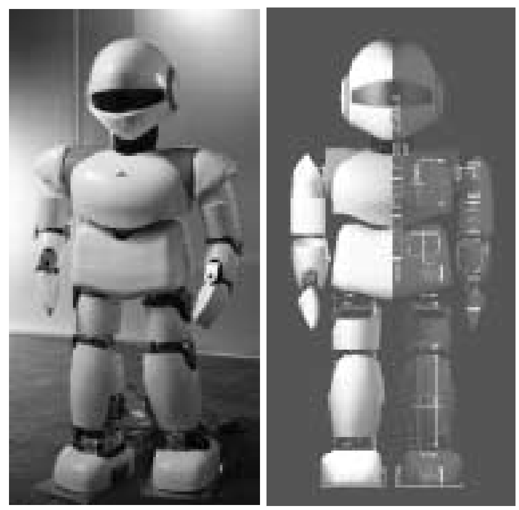

Figure 1: Picture and mechanism of PINO

1 Introduction

We have developed the humanoid PINO[1] which can be a low-cost humanoid platform for various research purposes. Figure 1 shows the whole view and the mechanical architecture of PINO.

PINO has the 26 DOFs (degrees of freedoms) and the actuator consist of low cost and off-the-shelf components. Especially, the actuators of PINO are servos for radio control model with a maximum torque of 1.96 [N·m].

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. Recently, many researchers have reported studies on biped walking[2][3][4][5]. It should be noted that most of the current control methods for humanoid walking are designed independently of the dynamics of the robot hardware. In general, these control methods require extremely large torque to realize the desired walking patterns. The use of dynamics of a mechanical platform may significantly reduce the need for high torque motors by attaining energy-efficient behavioral patterns.

McGeer, especially, has studied PDW (Passive Dynamic Walk), in which simple walkers can walk down a gentle slope without any actuators for controlling

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them[6], their walking motions are decided by the relationship between the 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[7]. These control methods for PDW make much use of the dynamics 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 with flexible 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[8].

Also, in an artificial life, Sims generated a robot which can walk, jump and swim in computer simulation, and generated virtual creatures which compete with each other to obtain one resource[9]. Ventrella introduced evolutionary emergence of morphology and locomotion behavior of animated characters [10].

Acquisition of highly energy-efficient humanoid walking locomotion should consider both mechanical configuration and control method simultaneously. In previous studies, we have proposed a simple control method for humanoid walking using hte dynamics of the robot with and without torso, and confirmed that this control method is valid for biped walking [11].

In this paper, therefore, we describe the mechanical design which can achieve highly energy-efficient walking using the proposed control method from the view point of maximum energy and energy consumption.

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 model with highest energy efficiency 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 links are 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. Each link has uniformly distributed mass m_1, m_2 and m_3

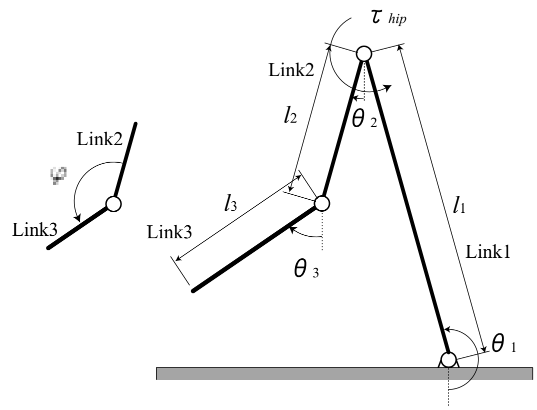

Figure 2: Planar 3 link model of the robot

respectively, and we define the density of each link as 3.2 [kg/m] and the length of link1 as 0.2785 [m], which are obtained by the parameters of PINO. We change the length of link3 from 0.1 [m] to 0.2 [m] by 0.01 [m] increments, and the length of link2 is decided by subtracting the length of link3 from link1.

We assume that every joint has a low 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.

2.2 The Control Method

In our previous study, we choose the control method represented by a moment of inertia on the hip joint I_{hip} as Equation 1:

$$\tau_{leg} = \begin{cases} -k_{leg}\varphi & (0 \leq t \leq t_1) \\ 0 & (t_1 < t \leq t_2) \end{cases} \tag{1}$$

where τ_{leg} denotes the feedback torque at the hip joint and k_{leg} denotes feedback gain, and the relationship between φ and I_{hip} is represented as follow,

$$\begin{aligned} I_{hip} &= \tfrac{1}{3}m_2 l_2^2 + \tfrac{1}{12}m_3 l_3^2 + m_3(x'^2 + y'^2) \\ x' &= l_2 sin\theta_2 + \tfrac{1}{2}l_3 sin\theta_3 \\ y' &= l_2 cos\theta_2 + \tfrac{1}{2}l_3 cos\theta_3 \end{aligned} \tag{2}$$

where x' and y' denote the center of gravity position of link3. From this equation, I_{hip} is represented as follow.

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

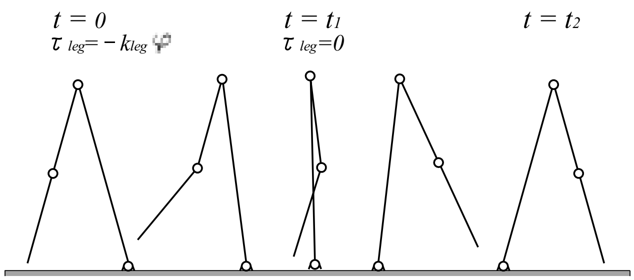

Figure 3: The motion phases of one cycle

Also, we assume the one step walking motion consists of two phases shown in Figure 3. In the first phase ($0 \leq t \leq t_1$), 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 ($t_1 < t \leq t_2$), the feedback torque τ_{leg} does not add to the hip joint. The swing leg moves forward freely until it collides with the ground. t_1 and t_2 are decided uniquely satisfying the law of conservation of angular momentum between immediately before and after foot collision shown in Equation. 4:

$$\left[I(\theta)^-\right]\left\{\dot{\theta}^-\right\} = \left[I(\theta)^+\right]\left\{\dot{\theta}^+\right\} \qquad (4)$$

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 right before and after foot collision. We assume that the collision at a knee stopper is a perfectly non-elastic collision. The dynamic equation of this three-link model can be represented as follow:

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

where $[M(\theta)]$, $[C(\theta)]$ and $[K(\theta)]$ denote the parameter matrices of the mechanism and angular positions of the links, and $[\tau]$ denotes feedback torque vector. In the previous study, this proposed control method enabled the robot to walk with high energy efficiency, and we confirmed that the robot can change the walking speed when we change the moment of inertia of the swing leg at the hip joint.

3 Simulation

In the proposed control method, it has been verified that changing k_{leg} enables a robot to change the walking speed with lower energy consumption. Figure 4 and 5 show the effect of k_{leg} on t_2 and relationship between I_{min} and t_2 respectively. In order to verify the effect of the link parameters of the robot, we fix the feedback gain k_{leg} as 0.15, and the angle of link1 aganst to a ground as 10.0 [deg]. The total foot length l_1 is fixed and the length ratio of the superior limb l_2 and inferior limb l_3 is changed. We change the length of link3 l_3 from 0.1 [m] to 0.2 [m] by 0.01 [m] increments under the effect of the gravity, and we perform simulation using the length ratio of link2 and link3 σ which calculated by equation 6.

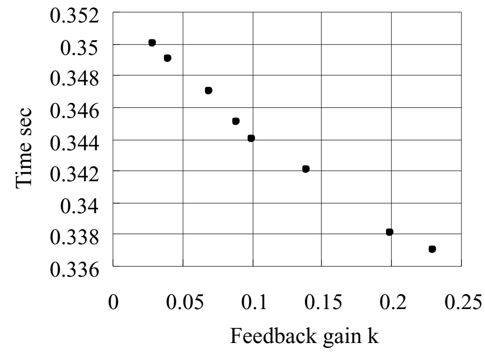

Figure 4: Effect of k_{leg} on t_2

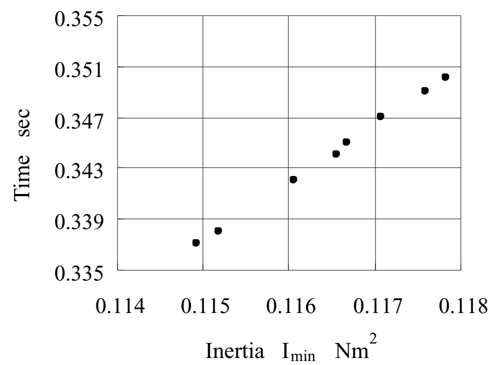

Figure 5: Relationship between I_{min} and t_2

$$\sigma = \frac{l_3}{l_2} = \frac{l_3}{0.2785 - l_3} \qquad (6)$$

Dynamical simulations are analyzed by a fourth Runge - Kutta method, and the time step is 0.2 [ms].

Simulations are performed foot gait, moment of inertia, maximum energy and energy consumption during one step motion.

4 Results and Discussion

4.1 Foot gaits

At first, we obtain the one step foot gait in each σ from simulation. Figures 6, 7 and 8 show the foot gait of $l_3 = 0.1$ ($\sigma = 0.53$), $l_3 = 0.15$ ($\sigma = 1.09$) and $l_3 = 0.18$ ($\sigma = 1.67$) respectively.

The minimum clearance to the ground of the swing leg is 0.0128 [m] at $\sigma = 0.53$, 0.0142 [m] at $\sigma = 1.09$ and 0.0145 [m] at $\sigma = 1.67$. The maximum clearance to the ground of the swing leg is 0.0380 [m] at $\sigma = 0.53$, 0.0337 [m] at $\sigma = 1.09$ and 0.0329 [m] at $\sigma = 1.67$.

From Figures 6, 7 and 8, it is verified that the foot tip gait of each σ is a similar trajectory, and the clearance of the swing leg to the ground in each σ is sufficient to make the robot walk.

From the view point of the foot gait, every σ can realize the suitable foot gait to make the robot walk.

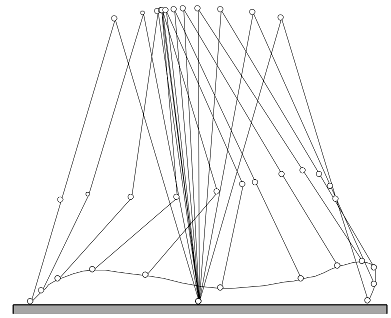

Figure 6: foot gait $l_3 = 0.1$ ($\sigma = 0.53$)

4.2 Effect of minimum moment of inertia on link length ratio

In the previous study, it was verified that we can use the minimum moment of inertia during one step walking I_{min} as a performance index of I_{hip}.

At first, we calculate I_{min} from Equation 2 using l_3 and φ.

$$I_{min} = f(l_3, \varphi) \quad (7)$$

Figure 9 shows the relationship between σ and I_{min} when φ is 15.0, 30.0, 45.0 and 60.0 [deg] calculated by Equation 7:

From Figure 9, the minimum moment of inertia I_{min} is always the smallest at $\sigma = 1.98$ in every φ. It is verified that the moment of inertia in the case of $\sigma = 1.98$ is a minimum value in every condition of the swing leg without the effect of gravity and any other disturbances.

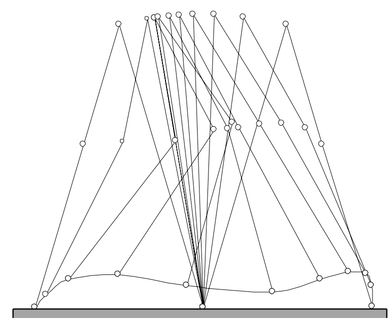

Figure 7: foot gait $l_3 = 0.15$ ($\sigma = 1.09$)

4.3 Effect of maximum energy on link length ratio

The total energy of a robot E is calculated by the following equation:

$$E = \sum_{i=1}^{3} \left(\frac{1}{2} m_i \dot{v_i}^T \dot{v_i} + \frac{1}{2} \omega_i^T I \omega_i + m_i g h_i\right) \quad (8)$$

where $\dot{v_i}$ and ω_i denote the translation velocity and rotation velocity of each links respectively, I is the inertia tensor, g is a gravitational acceleration, and h_i is the height of center of gravity of each links. Also,

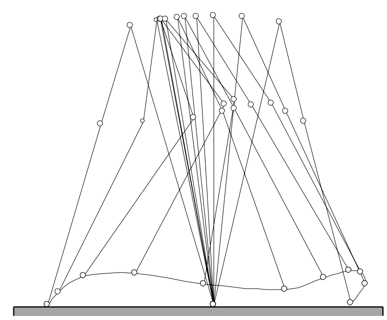

Figure 8: foot gait $l_3 = 0.18$ ($\sigma = 1.67$)

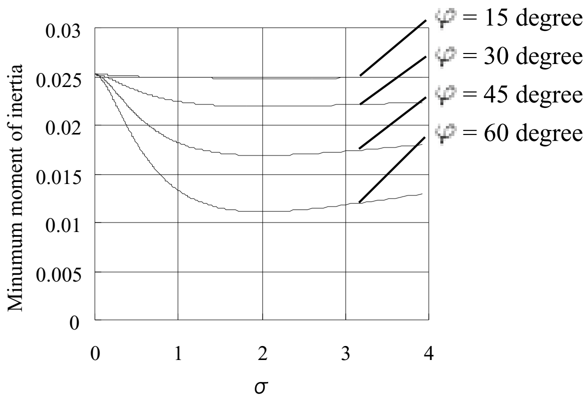

Figure 9: Effect of I_{min} on link length ratio

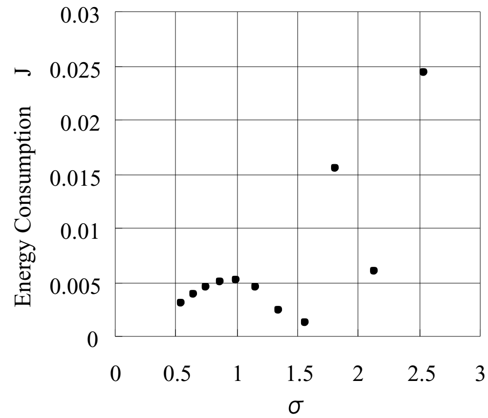

Figure 11: energy consumption

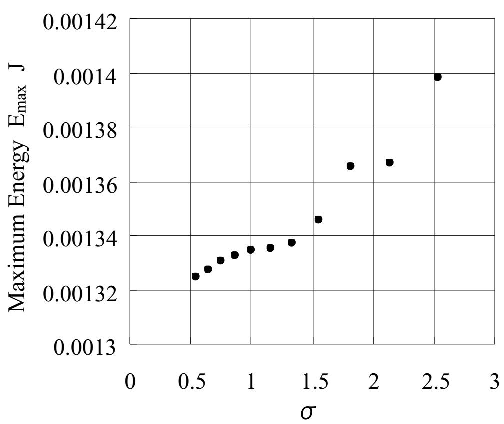

Figure 10: maximum energy

i denotes the link number. Figure 10 shows the relationship between σ and the maximum energy E_{max} during the one step walking.

For biped walking robots with low torque actuators, the maximum torque τ_{max} and the maximum energy E_{max} are some of the most important problems. In this time, the maximum torque at the hip joint τ_{max} is the same value in every σ because τ_{max} occurs at the initial position which φ is 180.0 [deg].

From Figure 10, it is clear that this relation consists of two kinds of curves and there is a boundary at the point of $\sigma = 1.5$. If the σ is larger, maximum energy increases exponentially.

Therefore, from the view point of maximum energy during one step walking, it is adequate to select a σ below 1.5.

4.4 Effect of energy consumption on link length ratio

The energy consumption $E_{consumption}$ can be represented as shown in Equation 9:

$$E_{consumption} = \sum_{i=1}^{3} \int_0^{t2} \tau_i \dot{\theta}_i \, dt \qquad (9)$$

where E_{init} denotes the initial potential energy, which is the same value at the final energy because of the law of conservation of angular momentum between immediately before and after foot collision, and t_2 is the time to touch down the swing leg to the ground.

Figure 11 shows the relationship between σ and the energy consumption $E_{consumption}$ during one step walking.

From Figure 11, this relation has a local minimum around $\sigma = 1.5$, and if σ is larger than 1.5, the energy consumption increases exponentially. Thus, a robot designed with a ratio of $\sigma = 1.5$ can walk with high energy efficiency using the proposed control method. From the view point of the energy consumption, this ratio is a little smaller than σ of PINO, which is about 1.63. In the minimum moment of inertia, the optimal σ is 1.96. But this σ doesn't consider the effect of gravity and any other disturbances. In this simulation, the model has joint viscosity. Therefore, it is assumed that the gap between these σ is caused by the effect of gravity and disturbances.

4.5 Effect of time to touch down on the link length ratio

It is verified that $\sigma = 1.5$ is optimal ratio of link length from the view point of maximum energy and

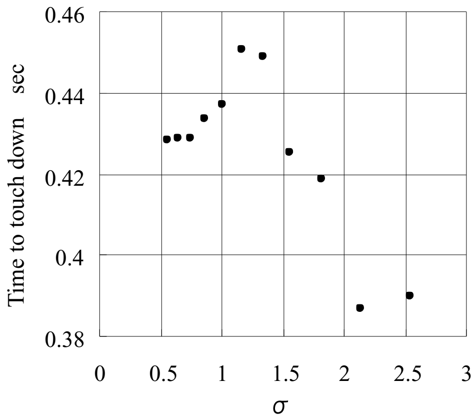

Figure 12: time to touch down

energy consumption. Besides, the time to touch down the swing leg to the ground in for each σ is shown in Figure 12.

From Figure 12, t_2 has a maximum value between $\sigma = 1$ and $\sigma = 1.5$.

In the biped walking robot, to achieve the walking motion with high energy efficiency requires walking with a proper period.

In general, to generate high torque with smaller actuators, we select further gear down actuators. But these actuators has low rotation and low response because of further gear down. Therefore, it is proper that the walking period is slower. Also, if the proper period of the walking motion is slower, the control of the robot is easier. Thus, we should select the slower period of the walking motion.

From the view point of time to touch down the swing leg to the ground, t_2 is proper between $\sigma = 1$ and $\sigma = 1.5$.

Further, it has been confirmed that this control method can change its walking speed when the the length ratio σ is changed without changing the step length.

Therefore, the robot can realize various kinds of walking patterns.

5 Extension

In previous section, the initial angle of link1 against to a ground as 10.0 [deg], therefore, the step length is decided uniquely as 0.0967 [m]. In this section, therefore, optimal step lengths of every length ratio are investigated. A initial angle of link1 against to a ground is changed from 5.0 [deg] to 15.0 [deg].

Figure 13, 14 and 15 show the effect of the step size on the length ratio, the effect of the step period on the step length, the effect of the energy consumption on the length ratio respectively.

From these results, it is verified that the optimal step size is 0.05 [m] and step period is 0.31 [sec], in order to make PINO walk whose length ratio is $\sigma = 1.63$, if PINO is constrained in two-dimension space. The step size enables PINO to walk with high energy efficience from the view point of energy consumption, step size and step period.

6 Conclusion

In this paper, we presented a mechanical design process which can achieve highly energy-efficient walking using the proposed control method. By designing the mechanical configuration of a robot considering the control method for biped walking, we do not only realize a highly energy-efficient biped walking but also can provide an optimal mechanical configuration theory of humanoids.

Most of the current control methods for humanoid walking are designed independently of the dynamics of the robot hardware. In general, these control methods require extremely large torque to realize the desired walking pattern. The use of the dynamics of a mechanical platform may significantly reduce the need for high torque motors by attaining energy-efficient behavioral patterns.

Obtaining the optimal mechanical parameters of a robot which is based on the proposed control method can achieve highly energy-efficient biped walking. We ran simulations under the effect of gravity to obtain the optimal length of each link from the view point of foot gait, minimum moment of inertia, maximum energy E_{max}, energy consumption $E_{consumption}$ and time to touch down the swing leg to the ground t_2.

As a result, from the view point of foot gait, every σ has sufficient clearance to walk. Also it is verified that the minimum moment of inertia at every σ is 1.96 without the effect of the gravity and any other disturbances. In the maximum energy during one step walking motion, it is adequate to select the σ below 1.5. From the view point of energy consumption, the robot which is designed at $\sigma = 1.5$ can walk with high energy efficiency using the proposed control method.

Besides, the time to touch down the swing leg to the ground is proper between $\sigma = 1$ and $\sigma = 1.5$.

Considering these things, the optimal length ratio of the upper limb and lower limb under the proposed

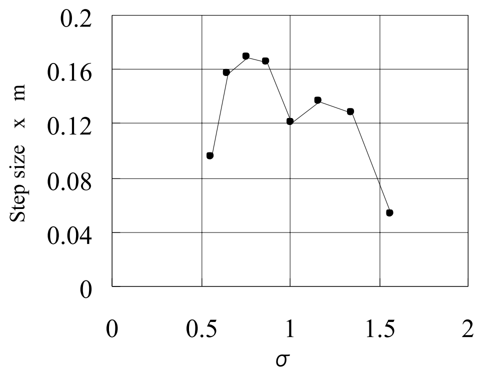

Figure 13: Effect of the step size on the legnth ratio)

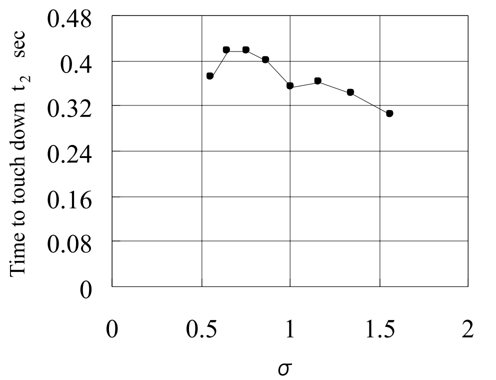

Figure 14: Effect of the step period on the length ratio)

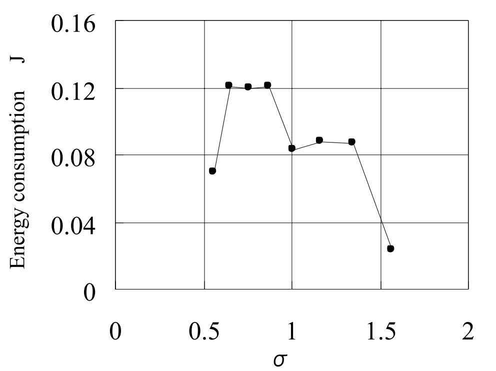

Figure 15: Effect of the energy consumption on the length ratio)

control method for biped walking is proper about $\sigma = 1.5$ under the effect of the gravity.

Therefore, a robot which is designed with $\sigma = 1.5$ and using the proposed control method can realize the highly energy-efficient biped walking, and we can find the optimal mechanical design parameters for biped walking which match the proposed control method.

In the future, we intend to obtain a four-link model with torso and to expand this control method to three-dimension space.

Also, we aim to achieve various kinds of stable walking patterns for PINO with low torque actuators.

7 Acknowledgements

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