Learning Energy Efficient Walking with Ballistic Walking

Masaki Ogino[1], **Koh Hosoda**[2] **and Minoru Asada**[3]

Dept. of Adaptive Machine Systems, Graduate School of Engineering,
[2,3]HANDAI Frontier Research Center,
Osaka University,Suita, Osaka, 565-0871, Japan,
e-mail: [1]ogino@er.ams.eng.osaka-u.ac.jp, {[2]hosoda, [3]asada}@ams.eng.osaka-u.ac.jp

Abstract

This paper presents a method for energy efficient walking of a biped robot with a layered controller. The lower layer controller has a state machine for each leg. The state machine consists of four states: First, constant torque is applied to hip and knee joints of the swing leg. Second, no torque is applied so that the swing leg can move in a ballistic manner. Third, a PD controller is used so that the certain posture can be realized at the heel contact, which enables a biped robot to walk stably. Finally, as the support leg, hip and knee joints are servoed to go back and the torque to support upper leg is applied. With this lower layer controller, parameters that enable robot to walk as energy efficiently as human walking can be searched by the upper layer controller without paying any attention to fall down.

1. Introduction

Comparing with human walking, bipedal walking of a robot is rather rigid. It is mainly because currently realized robot walking does not utilize natural dynamics while human walking does. Passive dynamic wakling (PDW) is one approach to realize natural motion in a robot. PDW is the walking mode in which a robot can go down a shallow incline without any control nor any actuation, only with its own mechanical dynamics [5]. This walking looks so similar to human walking that many researchers have been interested in it, and that its characteristic features and the conditions that enable a robot to walk in a PDW manner have been intensively studied [2, 3, 8, 9, 10, 13]. However, although PDW teaches us that mechanical dynamics of a robot can reduce control efforts for walking, the structural and initial conditions to realize PDW are strictly limited, and it is not always known how we can apply PDW properties to walking on a level floor. The properties that a controller should have in order to realize both stable and energy efficient walking simultaneously are not known yet.

We suppose that one of such properties is to have a control phase in which no torque is applied to a robot, which is called ”ballistic walking”. Ballistic walking is supposed to be a human walking model suggested by Mochon and McMahon [6]. They got the idea from the observation of human walking data, in which the muscles of the swing leg are activated only at the beginning and the end of the swing phase.

There are many methods to realize ballistic walking. Taga proposed a CPG controller that enables a human model to walk very stably with as the same energy efficiency as human walking [14]. The torque profile of his model shows the ballistic properties cleary. But his CPG model is very complicated and it is not always necessary to use CPG to realize energy efficient walking in a robot if the same properties are realized with a simpler controller. Actually, Linde shows that the energy efficient walking can be realized by a simple controller in which muscle contraction is activated by sensor information of foot contact [4]. But, he uses a very simple model without knees and torso. Recently, Pratt demonstrated in simulation and in a real robot that energy efficient walking is possible with a simple state machine controller, in which the knee joint of the swing leg is passively moved in the middle of the swing phase [11]. But he determined the parameters of walking by hand coding and genetic algorithm, and it is not clear the possibility to obtain the energy efficient walking with learning from non-efficient walking.

In this paper, to utilize dynamics of a robot, we let the hip joint free in the middle of the swing phase, and uses torque control instead of a PD controller in the beginning of the swing phase. Moreover, the learning module is added to the state machine controller so that the minimum energy walking can be realized.

The rest of the paper is organized as follows. First, the state machine controller to realize ballistic walking is introduced. Next, the learning module to optimize the parameters of the state machine controller is described. Then, the proposed controller is applied to a biped model which has the same length and mass to a human. Finally, a discussion is given.

2. Ballistic walking with state machine

Here, we use a robot model which consists of 7 links: a torso, two thighs, two shanks and two foots as shown in Fig.1. The parameters of the robot is shown in Table 1.

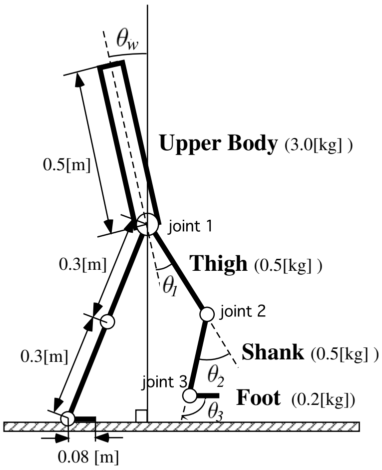

Fig. 1: Robot model

The state machine controller at each leg consists of four states, as shown in Fig 2: the beginning of the swing phase (*swing I*), the middle of the swing phase (*swing II*), the end of the swing phase (*swing III*), the support phase (*support*).

In the support phase, the hip joint is servoed by a PD controller so that the torso is made stand up and the support leg go back. To the knee joint, the torque is applied so that the knee joint becomes straighten during the support phase. Therefore, the torque is given by,

$$\begin{aligned}\tau_1 = -K_p(\theta_1 - \theta_{1d}) - K_v(\dot{\theta}_1 - \dot{\theta}_{1d})\\ -K_{wp}\theta_w - K_{wv}\dot{\theta}_w\end{aligned} \qquad (1)$$

and

$$\tau_2 = -K_p(\theta_2 - \theta_{2d}) - K_v(\dot{\theta}_2 - \dot{\theta}_{2d}). \qquad (2)$$

The reference trajectory for the above PD controllers are described with the simple sinusoidal functions which connect the angle of the beginning of the state to the desired angle which should be realized at the end

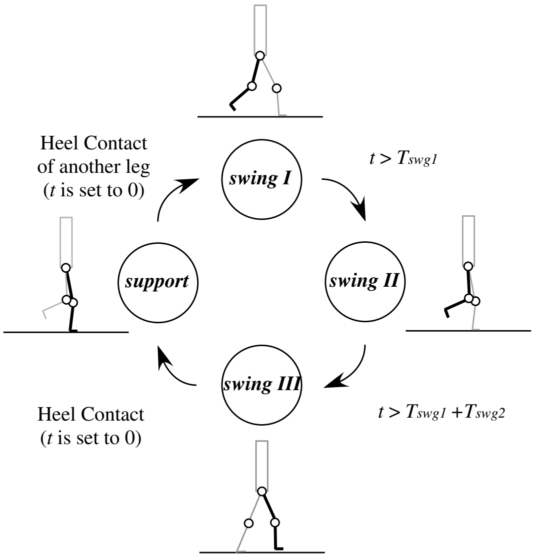

Fig. 2: A state machine controller consisting of four states

of the state,

$$\theta_{1d}(t) = \begin{cases} \frac{(\theta_{1e}-\theta_{1s})}{2}(1-\cos\frac{\pi t}{T_{spt}}) + \theta_{1s} & (t < T_{spt}) \\ \theta_{1e} & (t \geq T_{spt}) \end{cases}, \qquad (3)$$

$$\dot{\theta}_{1d}(t) = \begin{cases} \frac{\pi(\theta_{1e}-\theta_{1s})}{2T_{spt}}\sin\frac{\pi t}{T_{spt}} & (t < T_{spt}) \\ 0 & (t \geq T_{spt}) \end{cases}, \qquad (4)$$

$$\theta_{2d}(t) = \begin{cases} \frac{(\theta_{2e}-\theta_{2s})}{2}(1-\cos\frac{\pi t}{T_{spt}}) + \theta_{2s} & (t < T_{spt}) \\ \theta_{2e} & (t \geq T_{spt}) \end{cases} \qquad (5)$$

and

$$\dot{\theta}_{2d}(t) = \begin{cases} \frac{\pi(\theta_{2e}-\theta_{2s})}{2T_{spt}}\sin\frac{\pi t}{T_{spt}} & (t < T_{spt}) \\ 0 & (t \geq T_{spt}) \end{cases} \qquad (6)$$

where θ_{*s} indicates the angle at the moment when the controller enters the support phase (the moment of contact of the swing leg with the ground), and θ_{*e} indicates the desired angle that should be realized at the end of the support phase. t is the time since the controller enters to the support phase and T_{spt} is the desired time when the support phase ends. In this simulation, the control gains are set as $K_p = 300.0$ [Nm/rad], $K_v = 3.0$ [Nm sec/rad], $K_{wp} = 300.0$ [Nm/rad] and $K_{wv} = 0.3$[Nm sec/rad], and the desired angles of the end of the support phase are set as $\theta_{1e} = 20.0$ [deg] and $\theta_{2e} = 0.0$ [deg].

The swing phase is separated to three states; *swing I* (the beginning phase), *swing II* (the middle phase), and *swing III* (the end phase). In *swing I*, the controller applies constant torque to both the hip and knee joint. After the certain time passes, the control state changes to *swing II*, in which no torque is applied to the hip and knee joints. Therefore, in *swing II* the swing leg moves in a fully passive manner. After the swing time passes T_{swg2}, the control state changes to *swing III*, in which the joints are servoed using PD controllers so that the desired posture at the end of the swing phase can be realized. By taking a certain posture at the moment of ground contact, a certain degree of walking stability can be assured. The state of the controller transits to the state *support* when the swing leg contacts with the ground. The output torque can be summarized as the following equations,

$$\tau_1 = \begin{cases} A & (t < T_{swg1}) \\ 0 & (T_{swg1} \leq t < T_{swg1} + T_{swg2}) \\ -K_p(\theta_1 - \theta_{1d}) - K_v(\dot{\theta}_1 - \dot{\theta}_{1d}) & \\ & (T_{swg1} + T_{swg2} \leq t) \end{cases} \tag{7}$$

and

$$\tau_2 = \begin{cases} -B & (t < T_{swg1}) \\ 0 & (T_{swg1} \leq t < T_{swg1} + T_{swg2}) \\ -K_p(\theta_2 - \theta_{2d}) - K_v(\dot{\theta}_2 - \dot{\theta}_{2d}) & \\ & (T_{swg1} + T_{swg2} \leq t) \end{cases} \tag{8}$$

where the reference trajectory in *swing III* is given in the same manner as the support phase, eqs.(4)-(7). In our study, the desired angles of the hip and knee joints at the end of the swing phase are set as $\theta_{1e} = -20$ [deg] and $\theta_{2e} = 0$ [deg], respectively. T_{swg1} and T_{swg2} are set to 0.2 [sec], and 0.05 [sec].

Throughout walking, a PD controller with the weak gains ($K'_p = 3.0$ [Nm/rad] and $K'_v = 0.3$ [Nm sec/rad]) is used to the ankle joints,

$$\tau_3 = -K'_p(\theta_3 - \theta_{3d}) - K'_v(\dot{\theta}_3 - \dot{\theta}_{3d}) \tag{9}$$

The desired angle of the ankle joint is always fixed to 90 [deg]. Therefore, the ankle joint works as a spring is attached.

The simulation result of the controller is shown in Fig. 3, in which the resultant torque curves are shown with control mode during one period (two steps). In this figure, the control modes 1, 2, 3 and 4 correspond to *swing I, swing II, swing III and support*, respectively. In Fig. 3, large torque is observed at the end of the swing phase and the beginning of the support phase. This torque might be caused by too large or too small torque is applied at the beginning of the swing phase. If the appropriate torque is applied in *swing I* (at the beginning of the swing phase), this feedback torque might be lessen and the more energy-efficient walking could be realized. In the next section, the optimization of this torque is attempted by adding a learning module.

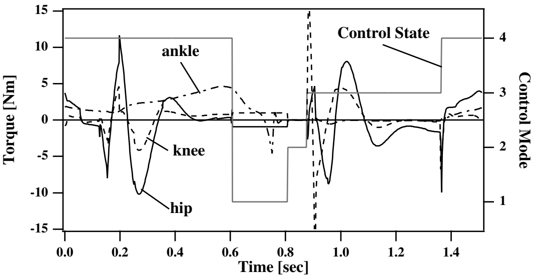

Fig. 3: State machine mode and torque during one period

3. Energy minimization with a learning module

To realize the energy efficient walking, a learning module which searches appropriate output torque in *swing I* is added to the controller described in the previous section (Fig.4). Besides torque, the learning module searches the appropriate value of control parameter which determines the end of the duration of passive movement, T_{swg2}. It is noted that these parameters are not related to the PD controller which stabilizes walking. For the evaluation of energy efficiency, we use the average of all the torque which is applied during one walking period (two steps),

$$Eval = \frac{1}{T_{step}} \int_0^{T_{step}} \sum_{i=1}^{3} \tau_i dt \tag{10}$$

Using this performance function, the appropriate values of the parameters are searched in the probabilistic rapid ascent algorithm as follows.

```
$if(Eval < Eval_{min})$
    $A_{min} = A$
    $B_{min} = B$
    $T_{swg2min} = T_{swg2}$
$A = A +$ random perturbation
$B = B +$ random perturbation
$T_{swg2} = T_{swg2} +$ random perturbation
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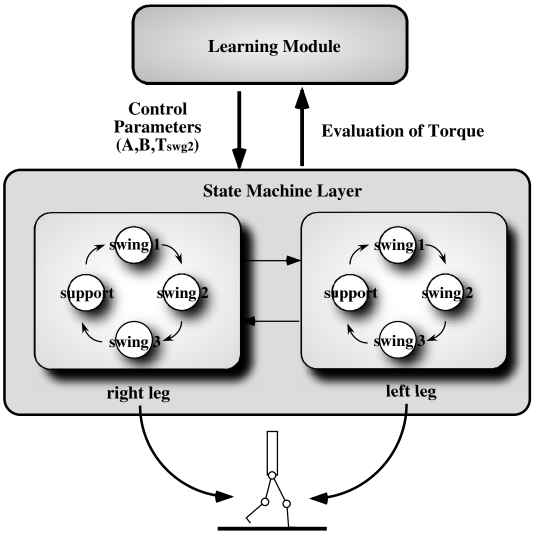


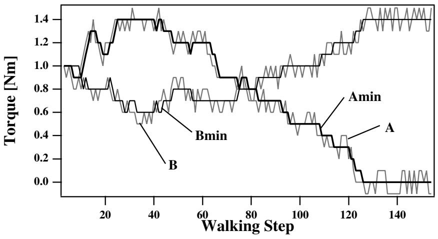
Fig. 4: Ballistic walking with learning module

The simulation results are shown in Fig. 5. Figures. 5 (a), (b) and (c) show the time courses of the output torque applied to the hip and knee joints in *swing1*, A, B, and the passive time, T_{swg2}, and the average of total torque, $Eval$, respectively. Even though the input torque changes variously, the PD controller in *swing III* which keeps the posture at ground contact constant realizes a stable walking.

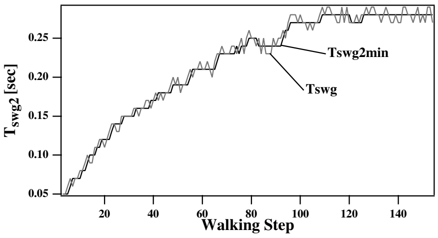
Comparing the first step with the 80th one, the average of total torque decreases (Fig. 5(c)), even though the output torque of the beginning of the swing phase at the 80th step is almost the same as the first step (Fig. 5(a)), whereas the passive time, T_{swg2}, increases (Fig. 5(b)). The total torque of walking, therefore, depends more on the passive time than the magnitude of the feedforward torque which is given in the beginning of the swing phase.

Furthermore, in the final stage of learning, after the 120th step, the output torque of the hip joint at the beginning in the swing phase becomes zero while that of the knee joint increases. It might be a strange result because many researchers have applied torque to hip joint in swing phase. In this stage, the large energy output appears among weak ones (Fig. 5(c)). This may be because robot walk on a wing and a prayer on the subtle balance between dynamics and energy. Once the balance is lost, the PD controller compensates stability with large torque.

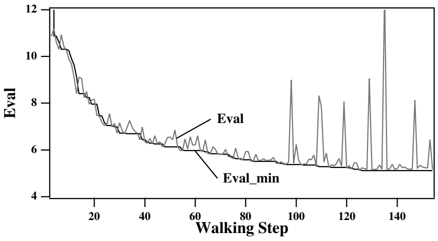
Fig. 6 is the time-course of the torque in around the 80th step. Comparing the torque appeared in Fig. 6 with those in Fig. 3, the maximum torque are reduced about 1/10 in the hip and knee joints, whereas



(a) torque



(b) T_{swg2}



(c) Average of Total Torque

Fig. 5: learning curve of control parameters and total torque

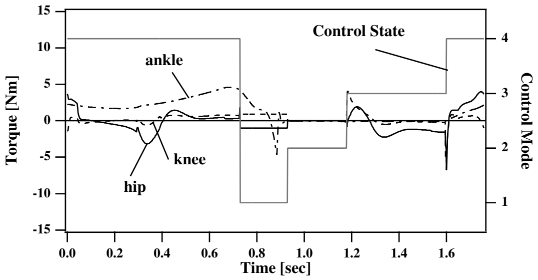


Fig. 6: State machine mode and torque by a state machine controller with a learning module

	Mass [kg]	Length [m]	Inertia [kg m^2]
HAT	46.48	0.542	3.359
Tigh	6.86	0.383	0.133
Shank	2.76	0.407	0.048
Foot	0.89	0.148	0.004

Table. 1: Mass and length of human model links

	Human	Simulation
Support : Swing [%:%]	60:40	60:40
Walking Rate [steps/sec]	1.9	1.3
Walking Speed [m/sec]	1.46	0.46
Walking Step [m]	0.76	0.36
Energy Consumption [cal/m kg]	0.78	0.36

Table. 2: Characteristics of simulation and human walking

the torque profile at the ankle joint is almost the same.

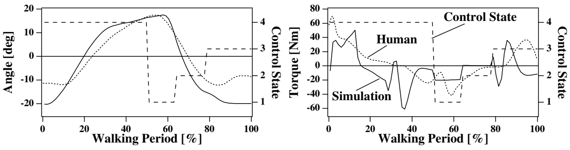
4. Comparing with human data

In this section, we apply the proposed controller to the model which has the same mass and length of links as human, and the torque and angle of each link are compared with the observed data in human walking.

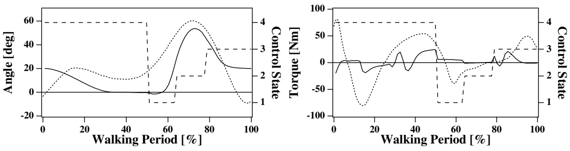
For parameters of human model, we use the same model as that of Ogihara and Yamazaki [7], which is shown in Table 1. The control gains at hip and knee joints are set as $K_p = 6000.0$ [Nm/rad], $K_v = 300.0$ [Nm sec/rad], $K_{wp} = 6000.0$ [Nm/rad] and $K_{wv} = 100.0$[Nm sec/rad]. The desired angles at the end of the swing and support phases are the same as in Section 2.

The time course of angle and torque of the simulation results are shown in Figs. 7 with human walking data (from [15]). The horizontal axis is normalized by the walking period.

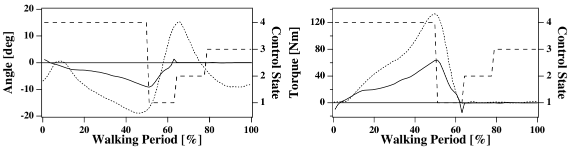
At the hip joint, while the time course of joint angle is almost same as human, that of torque is different, especially in around 80% and 30% walking periods in which strong effects of PD controllers appears (Fig. 7(b)). At the knee joint, the pattern of the time course of joint angle roughly resembles human data in shape except at around the end of the swing phase and the beginning of support phase, in which the knee joint of human data becomes straighten but that of simulation data not. Moreover, the torque pattern is quite different from human data. At the ankle joint, it is surprised that the torque pattern shares common traits with human data, even though the ankle joint is modled as simple spring joint. Fig. 7(f) shows that, although the control state after the support phase is named ”swing I”, it works as double support phase. The rate of swing phase to support phase is the same as human data (40:60).



(a) angle at hip joint (b) torque at hip joint



(c) angle at knee joint (d) torque at knee joint



(e) angle at ankle joint (f) torque at ankle joint

Fig. 7: Comparing with human walking data

Table 2 compares characteristic features of walking in the simulation result with that in human data ([12]). It shows that the simulation algorithm succeeds in finding the parameters which enable the human model to walk with 45% less energy consumption. But this walk may not necessarily mean the energy efficient walking because the walking speed (and the walking rate) is much slower than human walking. This may be because the proposed controller uses the ankle joint only passively, and only the energy consumption is taken into consideration in the evaluation function (eq. 10). Acquiring fast walking is our future issue.

5. Discussion

Our controller has a state machine on each leg which affects each other by sensor signals. Even this simple controller enables a biped robot to walk stably. There are two reasons. First, PD controllers at the end of the swing phase ensure that a biped touches down on the ground with the same posture. This prevents a swing leg from contacting with too shorter or too longer step length because of inadequate forward torque given at the beginning of the swing phase. But this stabilization does not always work well. It mainly depends on the posture at ground contact. How this posture is determined is the issue we should attack next.

The second reason for stable walking is that the controller has some common features to CPG (Central Pattern Generator). In CPG model, the activities of neurons are affected by sensor signals (or environment), and as a result global entrainment between a neural system and the environment takes place [14]. Our proposed controller doesn't have a walking period explicitly. The period of the controller is strongly affected by the information from touch sensors, which determine the state transition of a state machine in each leg. It can be said that our controller has some properties like global entrainment between state machine controller and the environment.

Walking mode realized in this paper is much slower than human walking as shown in Table 2. We think that the reason of this slow walking owes to the passive use of the ankle joint. To realize fast walking, it is necessary to shorten the walking period and to make the step length longer. They are closely related to the ankle joint setting because the speed of falling forward of support leg is largely affected by the stiffness of the ankle joint, and the steplength can be longer if the support leg rotates around the toe. Controlling the walking speed is another issue to be attacked.

Acknowledgments

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