Yet Another Humanoid Walking
— Passive Dynamic Walking with Torso under Simple Control —

Masaki Haruna   Masaki Ogino   Koh Hosoda   Minoru Asada

Dept. of Adaptive Machine Systems
Osaka University
Suita, Osaka, 565-0871, Japan

Abstract

Passive Dynamic Walking (PDW) has been receiving increasing attention as a simple walking method with no or less control, therefore no or less energy consumption. To the best of our knowledge, there are no PDW models with a torso although there have been already many studies on PDW. This paper presents the first step towards applying the PDW principle to humanoid robots by adding a torso to a conventional PDW model. The computer simulation shows that, only with a simple PD control applied between the torso and the stance leg to stand the torso up, the walking of the PDW robot converges at a stable gait cycle. Three attempts to reduce the torque to stand the torso up succeeded. Changing the mechanical properties of the robot itself with the same controller makes it possible to suppress the torque to stand the torso up: changing the posture of the torso, adding the soft leg tips, and changing the curvature of the sole. Computer simulation results are shown and discussion is given.

1 Introduction

Recently, there have been many humanoid robot projects, which have published their remarkable results. These approaches require very exacting work [4, 8]: they need strict strategies to plan trajectories very accurately, to control extremely precisely, and to adopt much powerful actuators. Many researchers have been studying to tackle these challenging strategies so far.

On the other hand, Passive Dynamic Walking (PDW) takes an extremely opposite approach to realize biped walking. A PDW robot can walk with simple strategies, that is, without any planning, any control nor any actuator. This is because a PDW robot fully utilizes the mechanical property of itself. This approach may cast new light on the biped walking of a humanoid robot left behind in the traditional approaches.

PDW is originally proposed by McGeer [5]. He demonstrated that a PDW robot could walk in a stable gait cycle both in computer simulations and in real experiments. Since then, many researchers have studied this topic. Garcia et al. [2, 3] showed the stability and chaotic character of PDW. Osuka et al. [7] demonstrated these characters in real robot. Recently, some researchers tried to make PDW robot walk not on a shallow slope but on a level floor [1, 6]. In these studies, however, a PDW robot has only legs. In order to apply PDW to humanoid robots, it is necessary to treat a PDW robot as similar as possible to a humanoid robot.

In this paper, we studied a PDW robot with a torso. Simulation results show that the PDW robot with the torso can walk in the stable gait cycle under a simple PD control applied between the torso and the stance leg to stand the torso up. We also investigated that, with the same simple control, the torque to stand the torso up can be suppressed by changing the mechanical properties of the robot itself.

The rest of this paper is organized as follows. In section 2, a PDW robot with a torso is introduced. In section 3, the stable gait cycles of the PDW robot under the simple PD control are demonstrated by simulations. In section 4, three methods to suppress the torque are shown: (1) changing the posture of the torso, (2) adding the soft leg tips, and (3) changing the curvature of the sole.

2 Passive Dynamic Walking Robot with Torso

In Fig.1, the PDW robot used in our work is shown. The robot consists of three rigid links and two joints: two leg links, one torso link, and two hip joints between the torso and each of leg link.

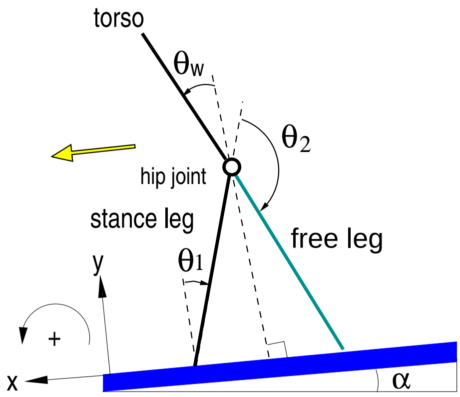


Figure 1: A passive dynamic walking model with torso. Variables θ_1 and θ_w are measured from ground-normal to each link, and θ_2 is measured from the extended line of the stance leg to the link of free leg. The y direction of base coordinate system is defined as slope-normal. The positive rotation is defined as counterclockwise.

A PDW robot which consists of only legs can walk down shallow slope in a stable gait cycle without any planning, any control, nor any actuator, only given appropriate initial leg angles and speeds. On condition that no torque is applied to stand the torso up, the appropriate initial conditions under which PDW is possible have not been found in our study so far. Probably, such a walking mode is considerably unstable, and even if these pinpoint conditions should be found on computer simulation, in real world we could not reproduce these conditions. Then, we decide to examine the possibility that a PDW robot with a torso can walk in a stable gait cycle when torque is applied with a simple PD control scheme given by,

$$\tau_w \quad = \quad -k_v\dot{\theta}_w + k(\theta_{wd} - \theta_w), \qquad (1)$$

where both k_v and k are the control gain, θ_{wd} is the desired angle of θ_w shown in Fig.1, and τ_w is the torque acting on the one hip joint between the torso and the stance leg. No torque acts on the other hip joint between the torso and the free leg, that is, the free leg is a completely passive links.

The floor force is calculated with spring-dumper contact model here, and it is assumed that the collision of the free leg is ignored while the free leg passes through the stance leg. The parameters of the links are indicated in Table1.

Table 1: Link name, parameter and values

name	parameter	value
leg length [m]	$l_f = 2r_f$	0.6
leg width [m]	-	0.03
leg mass [kg]	m_f	1.0
torso length [m]	$l_b = 2r_b$	0.5
torso width [m]	-	0.08
torso mass [kg]	m_b	3.0

3 Walking in Stable Gait Cycle under Simple Control

When the walking of the PDW robot with the torso under the simple control is started with leg angles and speeds within acceptable ranges, it settles down to a stable gait cycle at convergence point, as shown in Fig.2. In Fig.2, $\dot{\theta}_1$ and $\dot{\theta}_2$ indicate the angular velocity of the stance leg and the free leg just after the collision of each step, respectively. This graph shows the transitions of $\dot{\theta}_1$ and $\dot{\theta}_2$ started from a few examples of the appropriate initial conditions and the convergence point in a stable gait cycle.

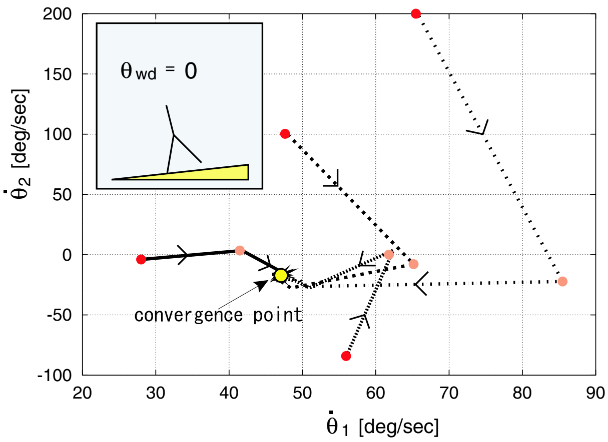


Figure 2: A convergence point of a stable gait cycle

It is interestingly that this stable gait cycle is changed with the same simple control by changing the desired value of the torso θ_{wd} as shown in Fig.3. In this graph, the numbers show the desired angles of the torso θ_{wd} [deg].

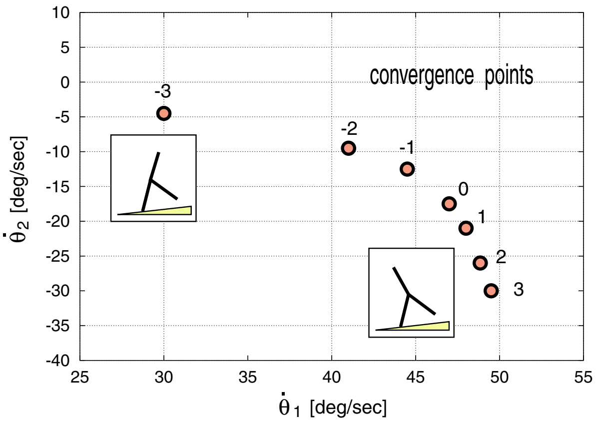


Figure 3: Convergence points in terms of the desired valued θ_{wd}

As the stable gait cycle is changed, the gait speed is also changed as shown in Fig.4 in which the desired angle θ_{wd} is represented on the horizontal axis and the gait speed on the vertical axis. As the torso inclines to backward, the gait speed slows down. This relationship can be utilized to suppress the torque to stand the torso up, which is described in the next section.

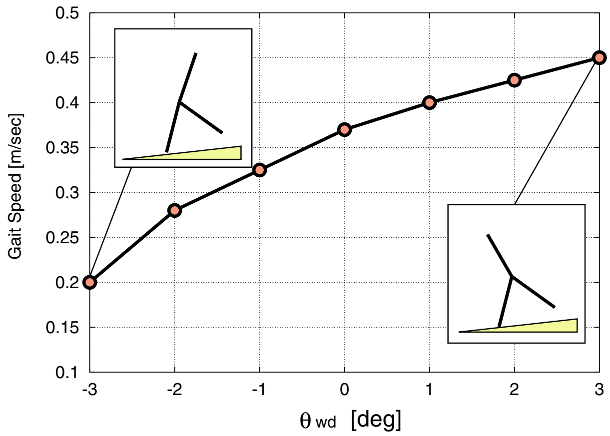


Figure 4: Gait speed vs. desired angle θ_{wd}

4 Torque Suppression by Changing the Properties

In order to decrease the energy consumption to stand the torso up with the same controller, the torque has to be suppressed without adding any complex control schemes. In this section, three attempts of the torque suppression are given. They are changes in the mechanical property of the robot itself.

4.1 Changing the posture of the torso

When the desired angle of the torso θ_{wd} becomes smaller, the gait speed slows down as described in section3. Consequently, the relative velocity of the free leg to the slope is decreased and thereby, the impact force at heelstrike is also decreased. These results are shown in Fig.5 in case of $\theta_{wd} = 3$, 0, and -3 [deg]. In these graphs, the desired angle of the torso θ_{wd} is represented on the vertical axis, and the velocity and the impact force at heelstrike on each horizontal axis.

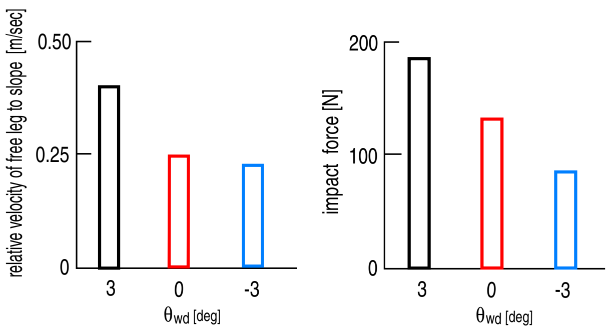


Figure 5: The relative velocity of the free leg to the slope and the impact force at heelstrike: According to the backward inclination of the torso, both the velocity and the impact force are decreased.

In connection with the backward inclination of the torso, the torque to stand the torso up at heelstirke is decreased. On the other hand, the torque in walking is not suppressed. Fig.6 shows the needed torque in case of $\theta_{wd} = 3$, 0, and -3 [deg]. In this graph, the torque, τ_w, is represented on the vertical axis, and the elapsed time on the horizontal axis. The curves are sifted in this graph due to the difference of each gait speed.

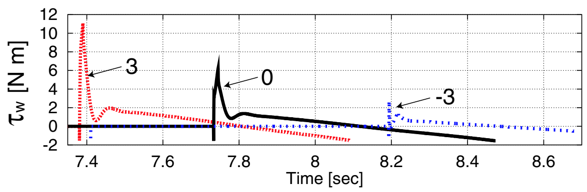
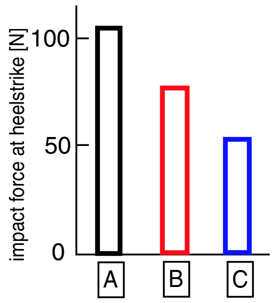


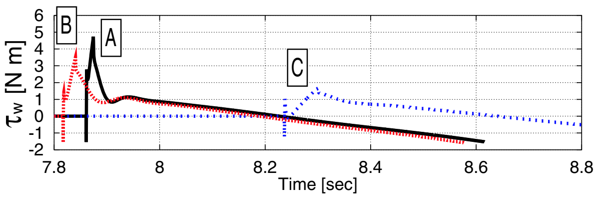
Figure 6: The torque suppressed at heelstrike by changing the desired angle of the torso.

4.2 Adding the soft leg tips

When the softer material is attached to the leg tips, the impact force is decreased more. Assuming the soft leg tips, the coefficients of spring-dumper contact model are adjusted. Simulation results show that, as the leg tips become softer, the needed torque at heelstrike is suppressed more, but the torque in walking is not suppressed. Fig.7(a) shows the impact force at heelstirke and Fig.7(b) shows the needed torque in case of three hardness of the leg tips labeled "A", "B", and "C". The label of "A" denotes the hardest leg tips, and the label of "C"softest leg tips of all three leg tips in each graph.



(a) The impact force



(b) The torque at heelstrike

Figure 7: The torque is suppressed more at heelstrike by changing the materials.

4.3 Changing the curvature of the sole

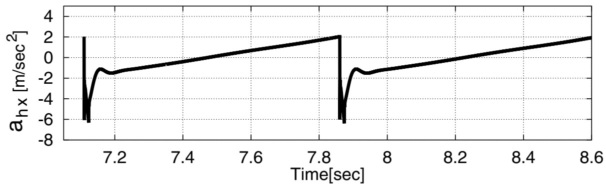
The torque τ_w applied to stand the torso up is needed for compensation of the rotational moment M_b around the hip point which consists of the inertial force $-m_b\boldsymbol{a}_h$ and the gravitational force $m_b\boldsymbol{g}$,

$$M_b \quad = \quad \boldsymbol{r}_b \times (-m_b\boldsymbol{a}_h + m_b\boldsymbol{g}), \tag{2}$$

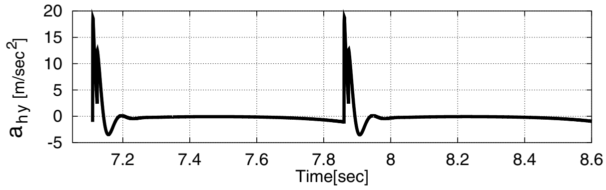
where $\boldsymbol{a}_h$ is an acceleration of the hip point, $\boldsymbol{r}_b$ is a vector from the hip point to the center of mass of the torso, and the other parameters are shown in Table1. Eq.(2) is expanded as follows,

$$\begin{aligned} M_b \quad = \quad & -m_b r_b\{\cos\theta_w(a_{hx} + g\sin\alpha) \\ & -\sin\theta_w(a_{hy} - g\cos\alpha)\}, \end{aligned} \tag{3}$$

where a_{hx} is an acceleration of the hip point along x direction, a_{hy} is an acceleration of the hip point along y direction, and α is an angle of the slope. Fig.8 shows the acceleration of the hip point along x and y direction during two steps. In walking, the acceleration of the hip point along y direction is almost zero. From Fig.8, and eq.(3), it can be said that M_b is most influenced by a_{hx}. This may conclude that the torque is most influenced by the acceleration of the hip point along x direction.



(a) Along x direction



(b) Along y direction

Figure 8: The acceleration of the hip point

According to the result described above, the structure should be changed to suppress the acceleration of the hip point along x direction a_{hx}. We investigate the effect of the sole on a_{hx} and the torque τ_w. To consider the effect of the curvature of the sole on a_{hx}, an inverted pendulum model shown in Fig.9 is proposed.

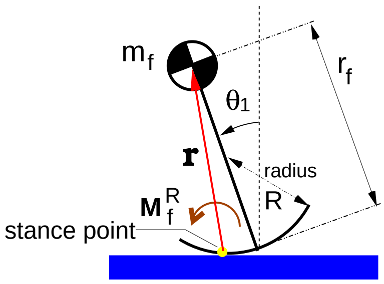


Figure 9: An inverted pendulum model to consider the effect of the sole on a_{hx}.

A moment of the model around the stance point M_f^R is calculated as,

$$\begin{aligned} M_f^R(R,\theta_1) &= \boldsymbol{r}(R,\theta_1) \times m_f \boldsymbol{g} \\ &= m_f g \sin\theta_1 (r_f - R), \end{aligned} \quad (4)$$

where $\boldsymbol{r}$ is a vector from the stance point to the mass of the model, r_f is a length of the pendulum, and R is a foot radius. This equation shows that the moment is a function of the radius of the sole R and the tilt angle of the model θ_1. When R is more than r_f, if θ_1 is negative, the moment around the stance point is counterclockwise, else clockwise. Therefore, the moment is exerted so that the inclination of the model θ_1 is zero. We may conclude that the effective radius of the sole to suppress the acceleration of the mass is larger than the distance r_f. Fig.10 shows the relationship between θ_1 on horizontal axis and M_f^R on vertical axis when R is 0.0 (solid line), and 0.8 [m] (dashed line).

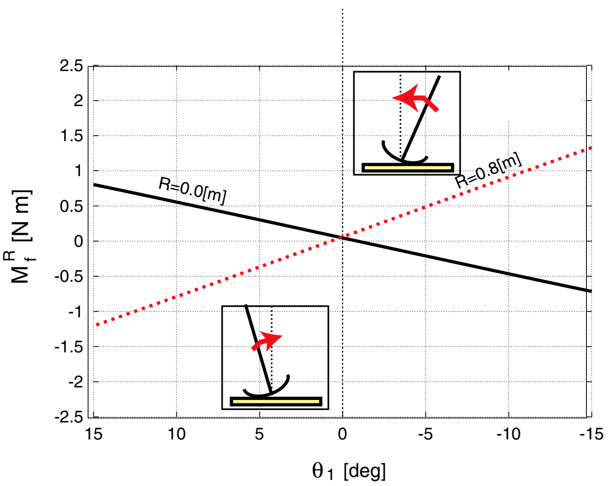


Figure 10: M_f^R: the moment determined by R and θ_1

Fig.11 shows the PDW robot with the torso and the sole. The radius of the sole is changed from 0 [m] to 1.2 [m]. When the radius is larger than 0.6 [m], foot contact phase and point contact phase appear. This is because that the length of the arc is kept constant value(0.16 [m]) in this simulation.

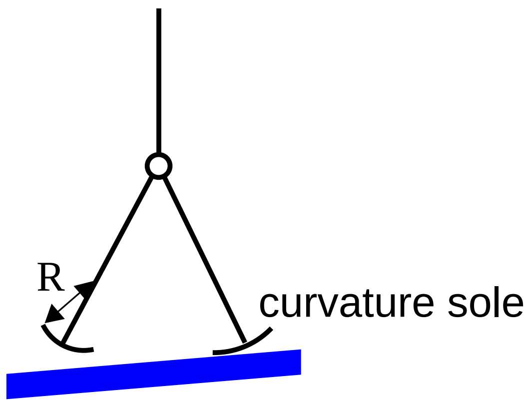


Figure 11: A PDW model with the soles. There are two contact phases: point contact phase and foot contact one.

When the radius of the sole is 0.8 [m], the acceleration of the hip point is suppressed to near zero during the foot contact as shown in Fig.12. This graph shows the acceleration of the hip joint along x axis during two steps. Compared with Fig.8(a) and Fig.12, especially foot contact phase and at heelstrike, the effect of the sole is evident.

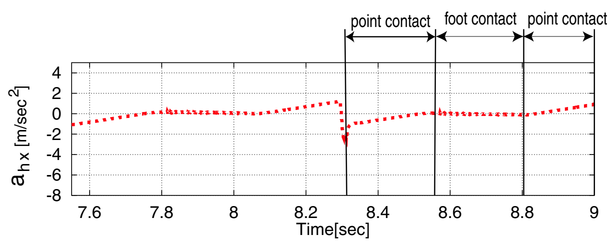


Figure 12: The acceleration of the hip point along x direction: R = 0.8 [m]

Consequently, the torque to stand the torso up is suppressed during foot contact phase and at heelstrike as shown in Fig.13. This is because that the soles make the acceleration of the hip point suppressed to near zero and the gait speed slowed down, too.

5 Conclusion and Future Work

In this paper, a PDW robot with a torso is examined. Simple PD control is applied between the torso

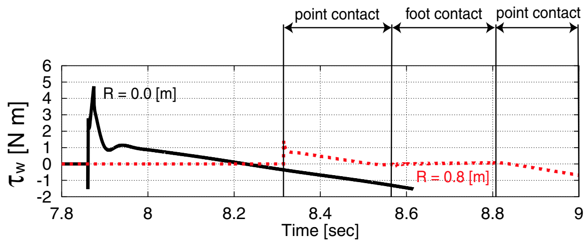


Figure 13: The torque suppressed during the foot contact and at heelstrike by changing the structure: the radius of the sole R = 0.8 [m]

and the stance leg in order to stand the torso up. Simulation results show that the PDW robot can walk in a stable gait cycle under simple control. It is also investigated that the torque to stand the torso can be suppressed by changing the posture of the torso, by adding the soft leg tips, and by changing the radius of the sole. Through these results, we demonstrate that a PDW robot with a torso can walk in a stable gait cycle only with a simple control scheme, and that the needed torque to stand the torso up is suppressed only by changing the mechanical properties of the robot itself.

Our final goal is to build a humanoid robot which can walk with simple strategies. We are currently studying the PDW robot with a torso and arms to compensate the moment around yaw axis, and planning to build a real robot based on these results.

References

[1] F. Asano, M. Yamakita, and K. Furuta. Virtual passive dyanmic walking and energy-based control laws. In *Proceedings of the 2000 IEEE/RSJ int. conf. on Intelligent Robots and Systems*, pp. 1149–1154, 2000.

[2] M. Garcia, A. Chatterjee, and A. Ruina. Speed efficiency and stability of small-slope 2-D passive dynamic bipedal walking. In *Proceedings of the 1998 IEEE int. conf. on Intelligent Robots and Systems*, pp. 2351–2356, 1998.

[3] M. Garcia, A. Chatterjee, A. Ruina, and M. Coleman. The simplest walking model:stability, complexity, and scaling. *Journal of Biomechanical Engineering*, Vol. 120, pp. 281–288, April 1998.

[4] Q. Li, A. Takanishi, and I. Kato. Learning control of compensative trunk motion for biped walking robot based on zmp stability criterion. In *Proceedings of the 1992 IEEE/RSJ int. conf. on Intelligent Robots and Systems*, pp. 597–603, 1992.

[5] T. McGeer. Passive dynamic walking. *The International Journal of Robotics Research*, Vol. 9, No. 2, pp. 62–82, April 1990.

[6] K. Ono, R. Takahashi, A. Imadu, and T. Shimada. Self-excitation control for biped walking mechanism. In *Proceedings of the 2000 IEEE/RSJ int. conf. on Intelligent Robots and Systems*, 2000.

[7] K. Osuka and K. Kirihara. Deveplopment and control of new legged robot quartet iii -from active walking to passive walking-. In *Proceedings of the 2000 IEEE/RSJ int. conf. on Intelligent Robots and Systems*, pp. 991 – 995, 2000.

[8] J. H. Park and H. Chung. Impedance control and modulation for stable footing in locomotion of biped robots. In *Proceedings of the 2000 IEEE/RSJ int. conf. on Intelligent Robots and Systems*, pp. 1786–1791, 2000.