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Learning of torque pattern generator for locomotion based on balance control

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Abstract: In this paper, we consider a torque pattern learning during biped walking based on the feedback balance control. By learning, the torque profile of feedback controller is copied to feedforward controller consisting of the oscillator. Then, the ground reaction forces, which are essential to behave in uncertain environmental conditions, are not required. We simulate this process under some environmental conditions.

Keywords: learning, balance control, torque pattern generation, periodicity of locomotion, oscillator

1. Introduction

In order to maintain the postural balance under the environment containing uncertainties, the feedback control is essential. Because the uncertain factors disturb the balance, and are usually unpredictable, the balance must be compensated by the feedback information. Such control mechanisms are found as the reflex in animals. During the locomotion, on the other hand, the physiological experiments with decerebrate and deafferented animals clarified that the rhythms for leg movements are basically generated by rhythm generators in the spinal cords[1)]. These findings imply the existence of neural oscillators that generate the rhythms in a feedforward manner in the sense that the rhythm generation is intrinsic and does not always necessitates the feedback information.

Of course, the rhythms for locomotion change with the environmental conditions. For the novel stationary environmental conditions, a new rhythmic pattern is stored (e.g. [2)]). During this learning process, the feedback information will takes important roles. From these observations, we can suggest the following scenario about the learning of the rhythmic locomotion pattern: In order to ambulate in uncertain environments, the feedback information is indispensable. However, if the uncertain environment is stationary, the uncertain factors are gradually clarified through the locomotion. As a result, the constant and adequate rhythmic pattern is generated, and finally learned in the rhythm generators. Once the rhythm pattern has been stored, it can be generated in an autonomous way without feedback information.

Based on this scenario, we here propose a mathematical model for learning the feedforward rhythm generation through the sensory feedback during walking.

2. Torque pattern learning for balance control

If the environment contains uncertain stationary factors, they may be identifiable due to their stationarity. Concentrating on this problem, we consider the static balance, i.e., upright posture control for a while. Afterwards, we extend this method to the locomotion control.

Among sensory information, ground reaction forces are crucial for the balance control. Especially, it is known that the zero moment point[3)], which is used as evaluation for the stability of the balance, coincides the center of pressure (CoP) of ground reaction forces[4)]. This is why we are focusing on the ground reaction forces to control the postural balance in the previous papers[5, 6)]. In this paper, we develop this method to store the periodic torque pattern of the locomotion into the pattern generator. So, in the remains of this section, we first review our previous papers.

2.1 Balance control under constant external force[5)]

At first, we consider the case where the unknown constant external force is exerted, whereby we express the uncertainties in the environment. To make an analysis simple, we consider a two-link model consisting of the body segment and the foot segment in the sagittal plane on a level ground, as shown in Fig. 1(a). The ankle is positioned at the center of the symmetrical foot segment to the anterior-posterior direction and as low as the ground surface. The foot segment contacts only on two points, the toe and the heel. If the balance is maintained, the foot segment does not move, and only the body segment shows the motion following the next motion equation:

$$\begin{aligned} I\ddot{\theta} &= MLg\sin\theta + F_xL\cos\theta - F_yL\sin\theta + \tau, \\ &= AL\sin(\theta - \theta_f) + \tau \end{aligned} \quad (1)$$

where M is the mass of the body segment, I is the inertial moment of the body segment around the ankle joint, L is the length between the ankle joint and the COG (center of gravity) of the body segment, θ is the ankle joint angle from the vertical direction, τ is the ankle joint torque, and g is the gravitational acceleration. F_x and F_y are the horizontal and vertical component of the unknown external force exerted to the COG of the body segment, respectively. A and θ_f are variables that satisfy the next equations:

$$A = \sqrt{(Mg - F_y)^2 + F_x^2} \quad (2)$$

$$\sin\theta_f = -\frac{F_x}{A}, \ \ \cos\theta_f = \frac{Mg - F_y}{A}. \quad (3)$$

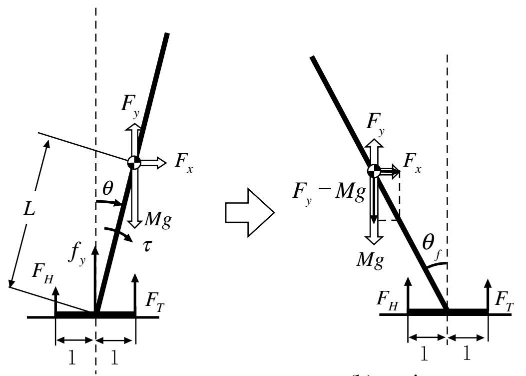


Figure 1: Model and stationary posture by control law (7).

The relation between the ankle joint torque τ and the vertical component of the ground reaction forces at the contact points, i.e., F_H, F_T, is represented as

$$F_H = \frac{1}{2\ell}\tau + \frac{1}{2}mg + \frac{1}{2}f_y, \tag{4}$$

$$F_T = -\frac{1}{2\ell}\tau + \frac{1}{2}mg + \frac{1}{2}f_y. \tag{5}$$

where ℓ is the distance from the ankle joint and the tip of the foot segment, m is mass of the foot segment and f_y is force from the body segment that is given as

$$f_y = -ML\ddot{\theta}\sin\theta - ML\dot{\theta}^2\cos\theta + Mg - F_y. \tag{6}$$

Here, we assume that F_x and F_y are constant. Under these conditions, we define the ankle joint torque τ as follows so that the total weight is evenly put on both toe and heel, i.e., $F_H = F_T$ are satisfied at the steady state:

$$\tau = -K_d\dot{\theta} - K_p\theta + K_f\int(F_H - F_T)dt. \tag{7}$$

Then, the posture where ankle joint angle takes θ_f becomes an equilibrium point, and if the feedback gain K_d, K_p and K_f satisfy

$$K_p > AL > 0 \tag{8}$$

$$\frac{\ell}{I}K_d > K_f > 0 \tag{9}$$

$$(K_d\ell - K_f I)K_p > K_d\ell AL \tag{10}$$

then this equilibrium point becomes locally stable.

2.2 Balance control under unknown periodic external forces with known period[6)]

In the previous section, we treated the balance control under the static external forces in the sense of their constancy. Here, we extend them to the dynamic case. Among them, we focus on the simplest situations, i.e., the ones where unknown external force, which is periodic and whose period is known, is exerted.

The significant feature of the control in the previous section is summarized to three items:

- The torque in the stationary state is zero, since the moment of the external force is cancelled out by that of the gravity. Thus, the stationary posture changes with the external forces.
- The ground reaction forces are essential information for such posture adjustments.
- The moment of the external forces, which was unknown at first, turns known by measuring the ankle joint angles at the stationary state.

The knowledges on the stationarity of environment obtained through the motion interacting with environment are informative to the future motion planning. If the environmental condition does not change, the postural balance will be achieved without the feedback of ground reaction forces since the adequate ankle joint angle are already obtained, i.e., we can set the desired angle for ankle joint a priori if the external force is known.

Following these consideration, we here aim at balance control that dispenses the feedback of the ground reaction forces, which is essential in the uncertain environment, by clarifying the unknown factors through the repetitive balancing motion under the periodic external forces. So, we construct the ankle joint torque as the summation of the feedforward term for the periodic external forces and the feedback term based on the ground reaction forces:

$$\tau = [F.F] + \left[-K_d\dot{\theta} - K_p\theta + K_f\int(F_H - F_T)dt\right] \tag{11}$$

Furthermore, we define the learning law of the first term in (11) so that the second term becomes zero.

The first term should not contain the information on the ground reaction forces, and will be constructed by estimating the periodic external force. Here, we assumed that the period of the external force, T_e, is known. Then, the external force can be expanded to the Fourier series whose fundamental frequency is $f_e = 1/T_e$.

$$F_x = \sum_k^n \left\{\alpha_k^{(x)}S_k + \beta_k^{(x)}C_k\right\} \tag{12}$$

$$F_y = \sum_k^n \left\{\alpha_k^{(y)}S_k + \beta_k^{(y)}C_k\right\} \tag{13}$$

where $S_k = \sin k\omega_e t$, $C_k = \cos k\omega_e t$ and $\omega_e = 2\pi f_e$. Substituting (12) and (13) to (1), we obtain

$$I\ddot{\theta} - MLgS - \sum_k^n \left\{\alpha_k^{(x)}S_k + \beta_k^{(x)}C_k\right\} LC + \sum_k^n \left\{\alpha_k^{(y)}S_k + \beta_k^{(y)}C_k\right\} LS = \tau \tag{14}$$

Here, $C = \cos\theta$ and $S = \sin\theta$. We can express the left hand side in the linear form to the known parameters.

$$Y\sigma = \tau \tag{15}$$

$$Y = \Big[\ddot{\theta}, S, S_0C, C_0C, S_0S, C_0S, \cdots, S_nC, C_nC, S_nS, C_nS\Big] \tag{16}$$

$$\sigma = \Big[I, -MgL, -L\alpha_0^{(x)}, -L\beta_0^{(x)}, L\alpha_0^{(y)}, L\beta_0^{(y)}, \cdots, -L\alpha_n^{(x)}, -L\beta_n^{(x)}, L\alpha_n^{(y)}, L\beta_n^{(y)}\Big]^T \tag{17}$$

Now, we define a new known parameter ϕ from σ as

$$\phi = K_I\sigma \tag{18}$$

$$K_I = \frac{K_d\ell}{K_d\ell - K_f I} \tag{19}$$

and give a control law using its estimates $\hat{\phi}$ as follows:

$$\tau = Y_r\hat{\phi} - K_d s \tag{20}$$

$$Y_r = \Big[\ddot{\theta}_r, S, S_0C, C_0C, S_0S, C_0S, \cdots, S_nC, C_nC, S_nS, C_nS\Big]^T \tag{21}$$

$$\dot{\theta}_r = -\frac{K_p}{K_d}\theta \tag{22}$$

$$s = \dot{\theta} - \dot{\theta}_r - \frac{K_f}{K_d}\tau_f \tag{23}$$

$$\tau_f = \int (F_H - F_T)dt \tag{24}$$

In addition, we define a learning dynamics for the known parameter ϕ as

$$\dot{\hat{\phi}} = -\Gamma Y_r^T s \tag{25}$$

where Γ is a positive definite diagonal matrix. Note that the first term of the right hand side in (20) contains no feedback of the ground reaction force, and the second term, $-K_d s$, is equal to the right hand side of (11).

Here, we set the following assumptions further more.

- A1 The periodic external force with known period T_e is bounded and differentiable.
- A2 In the initial state, the estimate of the unknown parameters are all zero, i.e., $\hat{\phi}(0) = 0$ and the ankle joint torque consists of only the second term, i.e., the left hand side of (7).
- A3 The foot never turns around from this initial state by this control law without the learning.
- A4 The foot does not turn around if the learning is applied to the conditions of A3.

Then, we can show that

- The second term containing the feedback of ground reaction forces are decreasing to zero.
- If $K_f \gg \ell$ is satisfied, the torque profile can be regarded as the same before and after learning.

These indicate that the following process. Initially, ankle joint torque consists of only the second term. Then the ratio of components is reversing to generate the torque only from the first term. Since the torque profile does not change by the learning, the second term is copied to the first term. It implies that the generation principle of torque pattern changes from the feedback to feedforward manner from the viewpoint of the information on ground reaction force.

3. Application to the locomotion pattern learning

3.1 Concept

In the previous section, we consider the balance control against the periodic external forces with known period. Here, we aim at applying it to learn the locomotion pattern.

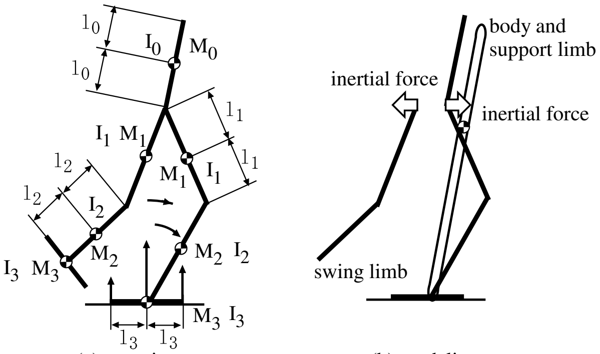
In locomotion, both the trajectory-tracking control and equilibrium control are important. The trajectory-tracking control is applied for the degrees of freedom (DoFs) whose reference trajectories are set in advance, e.g. for the posture of the body or the position of the foot where it should be put on. The equilibrium control, on the other hand, corresponds to the dynamic balance in the sense that the ZMP always stay within the sole of foot so that the foot segment does not turn around.

Here, we assume that the posture of the body or the reference trajectories of the swinging legs are planned in advance. When these reference trajectories are realized, the inertial forces produced from the movement of the legs or body will disturb the balance during the locomotion. The inertial force can be calculated based on the motion equations if the trajectories or mechanical parameters are known. The ZMP criterion is a method where such information on the inertial forces is utilized to compensate the balance by calculating the dynamics.

In this paper, however, we take another approach where the inertial forces are regarded as unknown disturbances; we do not calculate the motion equations to cancel out the inertial forces. We have set the assumption that the trajectories for tracking control are given, which implies that the duration of the inertial forces is known and that such inertial forces are periodically applied during the locomotion. Therefore, the inertial forces can be regarded as the periodic external force with known period, as treated in the previous section. From this point of view, we apply the method in the previous section to the balance control of the locomotion, and also aim at learning the locomotion pattern, i.e., the torque profile that maintains the balance during the locomotion.

3.2 A method

For the balance control, we here exploit the ankle joint torque, as shown in the previous section. Assuming that the changes in the inertial moment around the ankle joint is small during the locomotion, we regard the parts containing both the body and stance legs as the body segment in Fig. 1,



(a) notation (b) modeling

Figure 2: A link model for biped locomotion

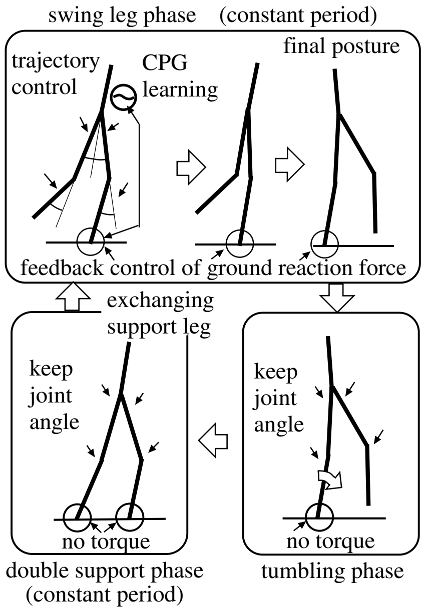


Figure 3: Control scheme.

as depicted in Fig. 2(b). Then the internal forces from the swinging leg correspond to disturbances.

As a rhythm generator, we introduce a harmonic oscillator producing sinusoidal functions in (16). The torque pattern will be internally generated as the weighted summation of the higher harmonic components of oscillator output.

3.3 Simulations

Control and learning As shown in Fig. 3, we define the three phases for the locomotion control, i.e., the double support phase, the swing leg phase, and the tumbling phase.

In the swing leg phase, the hip and knee joint of both swing and support legs are controlled to track their reference trajectories that are produced in advance by interpolating between given initial and final postures in the constant duration T_e. On the other hand, we apply the method in the previous section to control the balance using the ankle joint of the support leg. In parallel with the balance control, the torque pattern is learned to the pattern generator containing the oscillator.

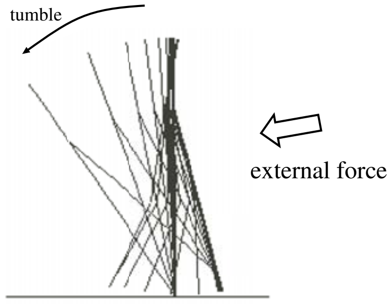


Figure 4: tunbling by external force.

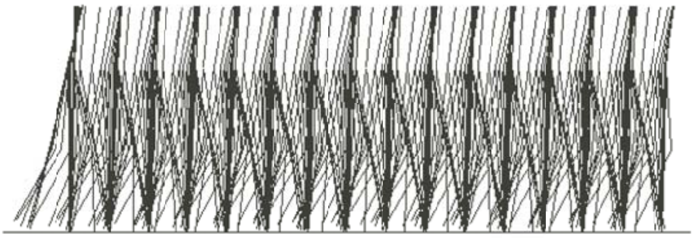
After the lapse of T_e, the phase goes to the tumbling phase. After the swing leg phase, the COG of the whole body usually comes forth to the ankle joint of the support leg, if the final posture is set so. Thus, if the torque of ankle joint is set to zero, the whole body makes a forward tumble. At the instance that the swing leg contacts to the ground, the phase goes to the double support phase.

In the double support phase, the hip and knee joint is kept constant during the constant period T_D to regain a balance. In the simulation, however, the hind support leg loses the contact to the ground due to the momentum of the tumbling. At this moment, the support leg is exchanged and the phase goes back to the swing leg phase.

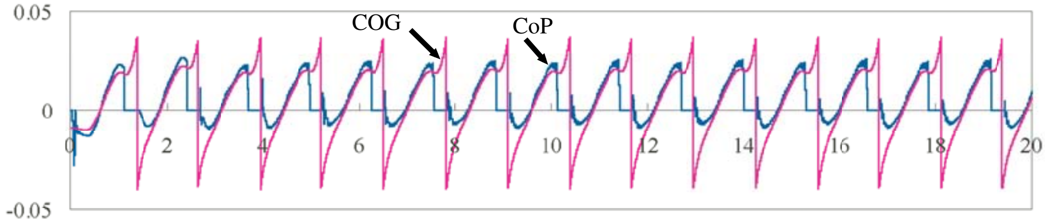
Conditions We simulate the locomotion on the level ground. The dynamics of the locomotion is calculated from a 7-link model consisting of the one-link body and 3-link legs, as illustrated in Fig. 2. To make the calculation simple, however, we assume the mass of the foot segment is smaller than any other segments in the body and so negligible. Thus we treated the dynamics as those of the 5-link mechanism in the simulations. The same parameter values of Fig. 2(a) are set in both left and right hand side as $M_0 = 2.5$, $M_1 = 1.5$, $M_2 = 1.0$, $M_3 = 0.0$, $l_0 = 0.06$, $l_1 = 0.08$, $l_2 = 0.08$, $l_3 = 0.05$ and $I_i = M_i l_i^2/3$.

In the below simulations, the feedback gains for the trajectory-tracing control are set as $K = 100$, $D = 10$, and the ones for balance control, $K_d = 14$, $K_p = 80$, $K_f = 0.12$. The parameters on the pattern generator are $n = 25$ and $T_e = 1.0$, i.e., the sinusoidal waves $\sin(2\pi kt), \cos(2\pi kt), (k = 0, \ldots, 25)$ are generated. Furthermore, the parameter of the learning speed is set as $\Gamma = diag[50, \ldots, 50]$. To express the contact between the foot segment and the ground, the ground is represented by the spring-dumper model, whose coefficients of the viscosity and elasticity are set as $D_g = 500$, $K_g = 50000$, respectively, in both horizontal and vertical directions. For the computation of the dynamics, 4th-order Runge Kutta method are used with the step size 0.001.

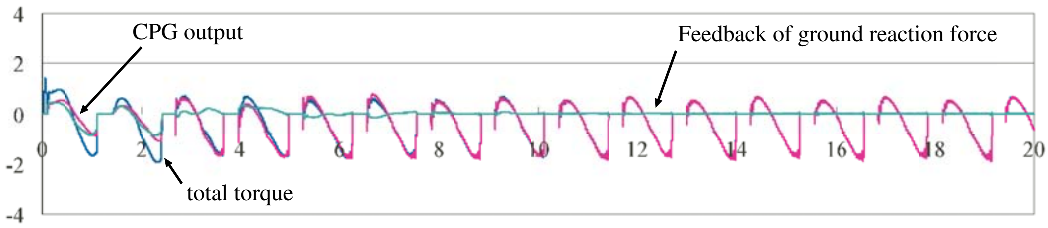
Effect of the feedback of ground reaction forces In the previous papers [5, 6], we suggested that the environmental conditions must be stationary in order to produce a constant motion pattern. As an example of the stationary environmental conditions, we introduced unknown constant external



(a) Walking motion.



(b) Position of CoP and COG.



(c) Ankle joint torque and its components.

Figure 5: Simulation of walking motion without external force.

forces. Now, we take the same method, i.e., we consider the case where the unknown constant external forces are exerted to all the links as follows,

$$F_i^{(x)} = -M_i g \sin\alpha \tag{26}$$

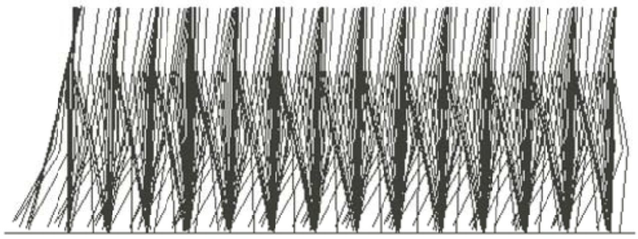
$$F_i^{(y)} = M_i g(1 - \cos\alpha) \tag{27}$$

Here, $F_i^{(x)}$ and $F_i^{(y)}$ express the horizontal and vertical component of the unknown external forces exerted to the i-th link, respectively. This is equivalent to the gravitational effect on the slope whose gradient is α

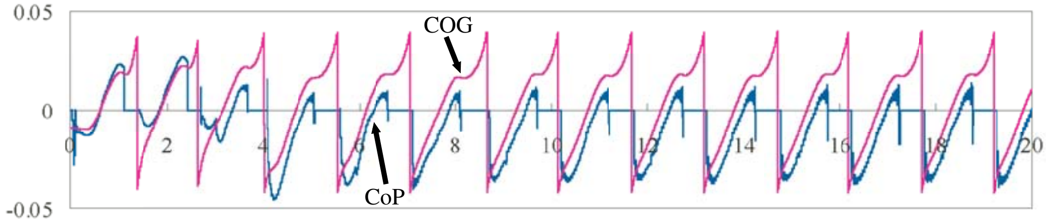
To show the effect of the feedback of ground reaction force, we compare the simulation results by setting $K_f = 0.12$ (with feedback) and $K_f = 0$ (without feedback). For $\alpha = 0$, the locomotion is achieved at both K_f values, since the trajectory of the hip and knee joint is set appropriately as it happens. However, changing α to 0.053 after the laps of 3.0 in another simulation, the link model with $K_f = 0$ tumbles backward due to the external force from the foreside, as depicted in Fig. 4. This result will be avoided by planning the suitable trajectory for the ankle joint. But, taking such control strategy, we are forced to plan the appropriate trajectories whenever the environmental conditions change. On the contrary, if the feedback of the ground reaction force is incorporated, i.e., $K_f = 0.12$, the replanning of the trajectories is not necessary: the ankle joint torque is produced so that it copes with the external forces (see next section).

Learning of locomotion pattern Firstly, we set $\alpha = 0$. The simulation results are shown in Fig. 5. The motion of the link model is illustrated in Fig. 5(a) with the stick diagram. The time courses of the CoP (i.e., ZMP) and COG position are depicted in Fig. 5(b). The length of the foot segment is $\ell_3 = 0.05$ for both back and forth direction. The CoP stays in this range, indicating no occurrences of tumbling during the locomotion. The ankle joint torques of the support leg as well as their components are depicted in Fig. 5(c). By continuing the locomotion in the stationary environment, the feedback component is gradually decreasing, whereas the output of the pattern generator is increasing to occupy the whole output after a while.

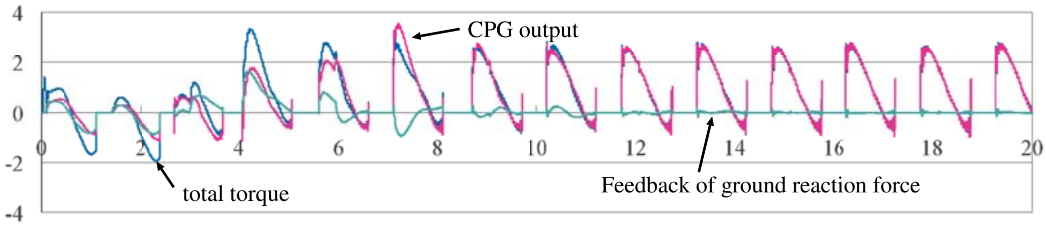
In the next simulation, we change α from 0.0 to 0.053 after the lapse of 0.3. The simulation results are shown in Fig. 6. In common with Fig. 5, the motion is drawn in Fig. 6(a), the time courses of CoP and COG are, Fig. 6(b) and the time courses of ankle joint torque as well as their components are, Fig. 6(c). Because of the constant external force from the front, the duration of the tumbling phase becomes



(a) Walking motion.



(b) Position of CoP and COG.



(c) Ankle joint torque and its components.

Figure 6: Simulation of walking motion with external force.

long, which elongates the locomotion period and inversely decreases the steps in the same simulation time comparing to Fig. 5(a). The trajectory of CoP stay within ± 0.05, indicating no occurrences of the tumbling, either. The torque profile of ankle joint in Fig. 6(c) differs from that of Fig. 5(c) due to the external force. Nevertheless, the different torque pattern is learned to the pattern generator by the same parameter settings.

4. Conclusion

We consider the learning method of locomotion pattern, i.e., torque profile for the balance through the walking motion. Because we applied our proposed method in the previous paper, the ankle joint torque is mainly used for the balance control, as is the same as there. However, as pointed out in the field of the walking robot control, there is a limit in the torque generation of ankle joint torque, which will restrict the application of our method. As future works, we must extend the DoFs for balance control from only ankle joint to other joints. And, we should introduce the entrainment of the rhythms between oscillator and mechanical dynamics that is the primal advantage of CPG control.

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