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The Cause of Natural Arm-swing in Bipedal Walking

Ying Wang[1], Yuichiro Toda[1], Mamoru Minami[1]

[1]Okayama University, Japan
(Tel:81-86-251-8233, Fax:81-86-251-8233)
[1]pskd42jr@s.okayama-u.ac.jp

Abstract: The research of humanoid is widely discussed whether by simulations or real machines. Our research purpose aims to reproduce the natural human movement. In human bipedal walking, swinging arms in opposite directions is a natural movement. In this research, a model of the humanoid robot, including slipping, bumping, surface-contacting and point-contacting of the foot has been established, and its dynamical equation is derived by the Newton-Euler method. And the natural arm-swing simulation has been produced, which showed that the input torque in yaw rotation of the torso could cause natural arm-swing. Based on the results, a hypothesis that the vibration in the yaw rotation of the torso caused natural arm swing is proposed. In this paper, we compared the arm-swing movement with or without the input torque of yaw rotation of the torso by using the above humanoid robot model. The simulation data proved the hypothesis correct by the Newton-Euler Method since the toque in the yaw rotation of the torso has different dynamic coupling on the left and right shoulder joints.

Keywords: Humanoid, Arm swing, Bipedal walking, Dynamical, Newton-Euler Method

1 INTRODUCTION

Human beings have acquired the ability of stable bipedal walking in evolving repetitions so far. Our research has begun from the viewpoint as aiming to describe gait's dynamics as correctly as possible, including point-contacting state of foot and toe, slipping of the foot and bumping [1] [2]. Meanwhile, the landing of the lifting leg's hell or toe in the air to the ground makes a regular contact. Based on [3], the dynamics of humanoid can be modelled as a serial-link manipulator, including constraint motion and slipping motion by using the Extended Newton-Euler (NE) Method[4]. The NE method enables us to make a dynamical model of robots which is possible to calculate internal force and torque not generating real motion of robot manipulator. It seemed to be an advantage of the NE method that other methods do not have [5]. This merit can be applicable for propagations of constraint and impact force/torque when discussing humanoids walking based on strict dynamical models. In previous research [6], a walking model of the humanoid robot, including slipping, bumping, surface contacting and point-contacting of the foot discussed, and its dynamical equation derived by the NE method.

In this research, we focused on human's natural arm-swinging motions during the walking. Arm swing in human bipedal walking is a natural motion wherein each arm swings with the action of the opposing leg without any input torque in the shoulders. Studies on the role of arm swing consist mainly of analysis of bipedal walking models and treadmill experiments on human subjects[9]-[10]. Bipedal walking models of various complexity levels explained the effects of arm swing on human locomotion [11]-[12]. Whether arm swing is a passive, natural motion caused by the rotation of torso or is an active motion that requires active muscle work has been a critical discussion on arm swing that could illuminate its benefit and function.

In this paper, we used the rigorous physical humanoid model composed of 17-link and 18 joints that we mentioned above [6]. We found that when there was no input in the shoulder joint and the torso in bipedal walking, the arm-swing spontaneously in the same direction in a small range. While when we added the torque to yaw rotation of the torso, the symmetrical arm-swing appeared in the opposite direction. We will introduce how the yaw rotation of torso influences arm-swing through the dynamic coupling by Newton-Euler(NE) Method.

2 DYNAMICAL WALKING MODEL

2.1 Humanoid Model

In previous research [6], a walking model of the humanoid robot, including slipping, bumping, surface contacting and point-contacting of the foot discussed. Its definition is depicted in Fig.1. Table 1 lists length l_i [m], mass m_i [kg] of links and coefficient of joints' viscous friction d_i [N·m·s/rad], which are decided based on [7]. The equation of motion is derived following by NE formulation as:

$$\boldsymbol{M}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{h}(\boldsymbol{q}, \dot{\boldsymbol{q}}) + \boldsymbol{g}(\boldsymbol{q}) + \boldsymbol{D}\dot{\boldsymbol{q}} = \boldsymbol{\tau}, \qquad (1)$$

Here, $\boldsymbol{\tau} = [f_1, \tau_1, \tau_2, \cdots, \tau_{17}]$ is input torque, $\boldsymbol{M}(\boldsymbol{q})$ is inertia matrix, both of $\boldsymbol{h}(\boldsymbol{q}, \dot{\boldsymbol{q}})$ and $\boldsymbol{g}(\boldsymbol{q})$ are vectors which indicate Coriolis force, centrifugal force and gravity. When the supporting leg is slipping, the $\boldsymbol{D} = diag[\mu_k, d_1, d_2, \cdots, d_{17}]$ is a matrix which means coefficients between foot and ground, and $\boldsymbol{q} =$

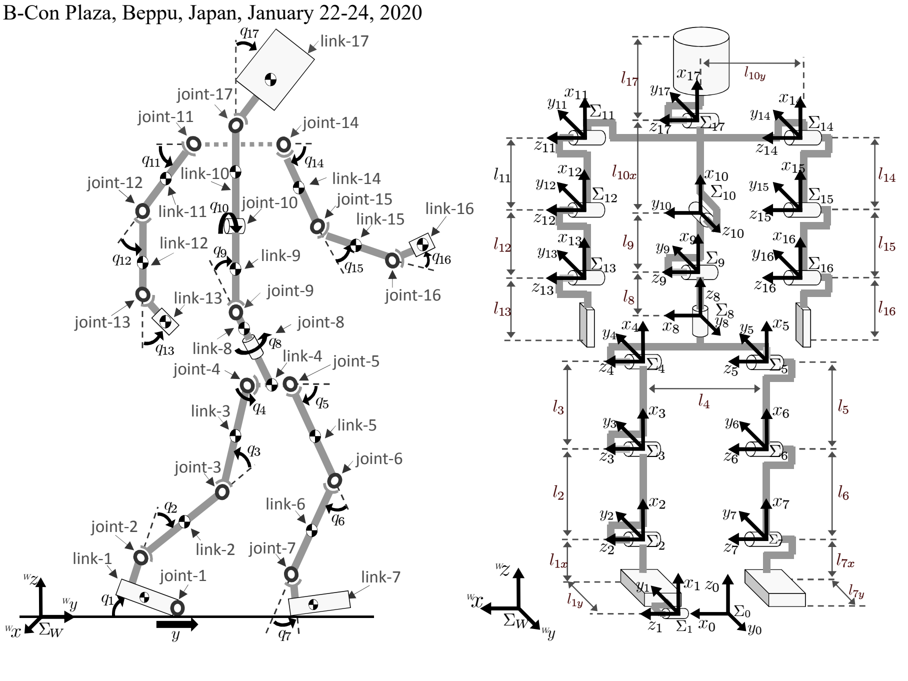

Fig. 1. Definition of humanoid's link, joint and coordinate system

Table 1. Physical parameters

Link	l_i	m_i	d_i
Head	0.24	4.5	0.5
Upper body	0.41	21.5	10.0
Middle body	0.1	2.0	10.0
Lower body	0.1	2.0	10.0
Upper arm	0.31	2.3	0.03
Lower arm	0.24	1.4	1.0
Hand	0.18	0.4	2.0
Waist	0.27	2.0	10.0
Upper leg	0.38	7.3	10.0
Lower leg	0.40	3.4	10.0
Foot	0.07	1.3	10.0
Total weight [kg]	—	64.2	—
Total hight [m]	1.7	—	—

$[y_0, q_1, q_2, \cdots, q_{17}]^T$ means the relative position between foot and ground and that of joints. Then, we have prepared 20 kinds of gait models according to the states and created the gait transition diagram shown in Fig.2. Based on it, we have realized bipedal walking in previous research. [5]

3 ANALYSIS OF ARM SWING

Out-of-phase arm swing is a typical pattern during human bipedal walking. The left-arm moves forward when the right leg and torso move forward, and vice versa for the opposing leg and arm. This arm motion, though natural, is not required for walking motion. For example, we can walk even while executing specific manual tasks which constrain the arms from swinging (e.g., holding an object with two hands or carrying a suitcase). However, without any particular manual objectives, the arm movements follow a consistent pattern. In this section, the reason for this natural arm motion is analyzed qualitatively from a dynamics perspective by using NE Method.

The angular acceleration of the shoulder joint directly determines the movement of the arm swing. From Eq.(1), we can calculate the angular acceleration of the right shoulder ($joint - 11$) and left shoulder ($joint - 14$) as the following equation.

$$\ddot{q}_{11} = \sum_{i=1}^{17} M^{-1}_{11,i}(\tau_i - b_i) \tag{2}$$

$$\ddot{q}_{14} = \sum_{i=1}^{17} M^{-1}_{14,i}(\tau_i - b_i) \tag{3}$$

Here, for $joint - i$, τ_i is input torque, $b_i$is the total of $\boldsymbol{h}(\boldsymbol{q}, \dot{\boldsymbol{q}})$ and $\boldsymbol{g}(\boldsymbol{q})$ and $\boldsymbol{D}$ which mean Coriolis force, centrifugal force, gravity and frictional force, respectively. As $joint - i$, when calculating $\ddot{q}_{11}$ and $\ddot{q}_{14}$, $\tau_i - b_i$ is the same. How much it affects the left, and right shoulder joints is determined by $M^{-1}_{14,i}$ and $M^{-1}_{11,i}$.

Using the control framework in previous research, our walking model of the humanoid robot can perform naturally human walking. And its dynamical equation is derived by the NE method so that it is possible to calculate internal force and torque of robot manipulator even not generating real motion.

To explore the reasons for the occurrence of the natural arm swing, an input torque of yaw rotation ($joint-8$) instead of the shoulder ($joint - 11$ and $joint - 14$) is added. The formula is as follows.

$$\tau_8 = \begin{cases} 30\sin(2\pi(t - t_e)/2) \\ (When\ supporting\ foot\ is\ right\ foot) \\ -30\sin(2\pi(t - t_e)/2) \\ (When\ supporting\ foot\ is\ left\ foot) \end{cases} \tag{4}$$

Simulations were conducted with or without τ_8. The data will be shown in the following section.

4 SIMULATION

Using the control framework in previous research, our walking model of the humanoid robot can perform naturally human walking. And its dynamical equation is derived by the NE Method so that it is possible to calculate internal force and torque of robot manipulator even not generating real motion. When proceeding to progressive walking, the friction coefficient between the foot and the ground is set to 0.7. According to Fig.3, we set gait transition as 1 → 2 → 6 → 10 → 18 → 1. This gait transition can realize the motion of the bipedal walking.

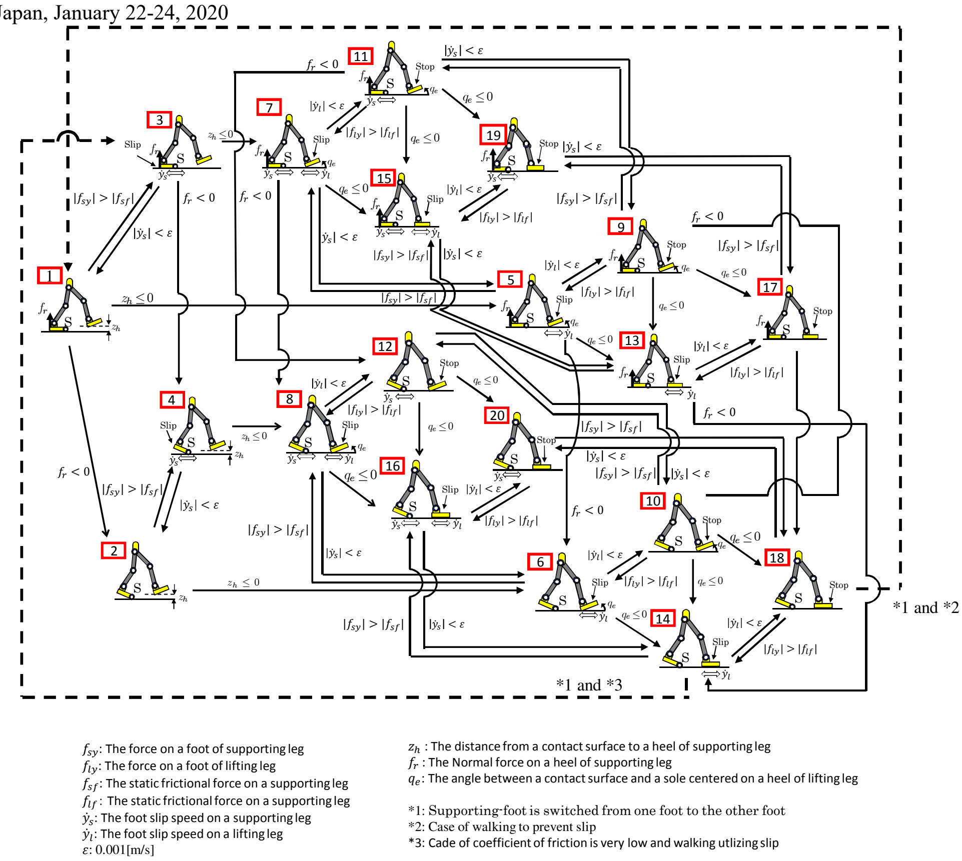

Fig. 2. Translation of bipedal walking

4.1 Simulation results

Simulations were conducted based on the experimental conditions shown in the previous section and were stopped at the time of 15s. Figure.3 and Fig.4 shows the arm angle and the screen-shot of the humanoid with/without τ_8.

When there was no input in both the yaw angle and the shoulder, Fig.3 shows that the synchronous arm-swing occurred in the same direction and a small range. When there is an input torque of yaw rotation ($joint-8$), even if the shoulder joint has no input torque, Fig.4 shows that symmetrical natural arm movement occurred during humanoid bipedal walking. So we make a hypothesis that vibration in the yaw rotation of the torso might be the reason to cause natural arm swing. In the next subsection, we analyze the data by NE Method and try to prove it.

4.2 Analysis of the data

To make a thorough inquiry into how the input toque of the yaw angle influences the arm swing by dynamic coupling, we took out the data of all the joints for analysis. Since our humanoid model has 18 joints, it is hard to show all of the data in this thesis. We divided the whole body joints into four parts to explore, as shown in Fig.1, the lower limbs (from $joint-1$ to $joint-7$), the torso (from $joint-8$ to $joint-10$), the upper limb (from $joint-11$ to $joint-16$) and the head. Only representative figures will be shown in this section.

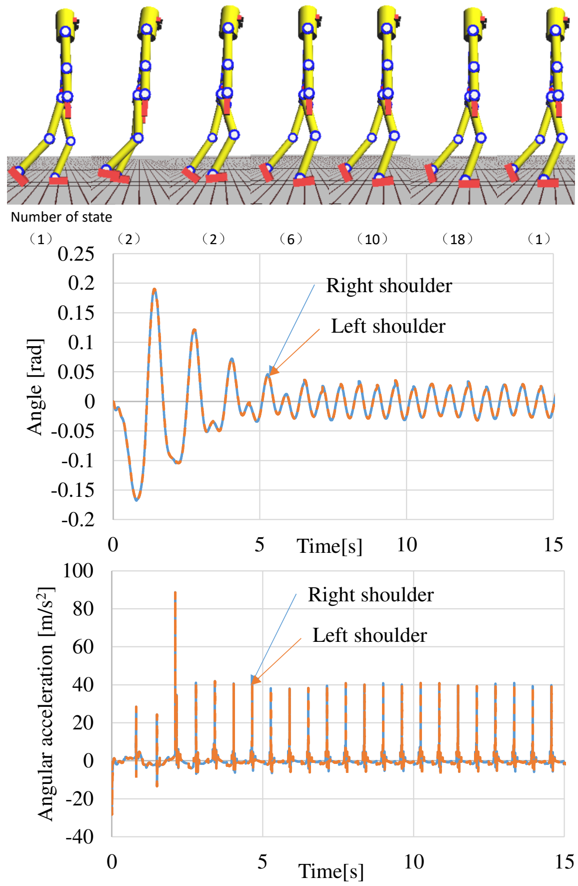

Fig. 3. Screen-shot and the angle/the angular acceleration when no input torque in the yaw rotation and the shoulder

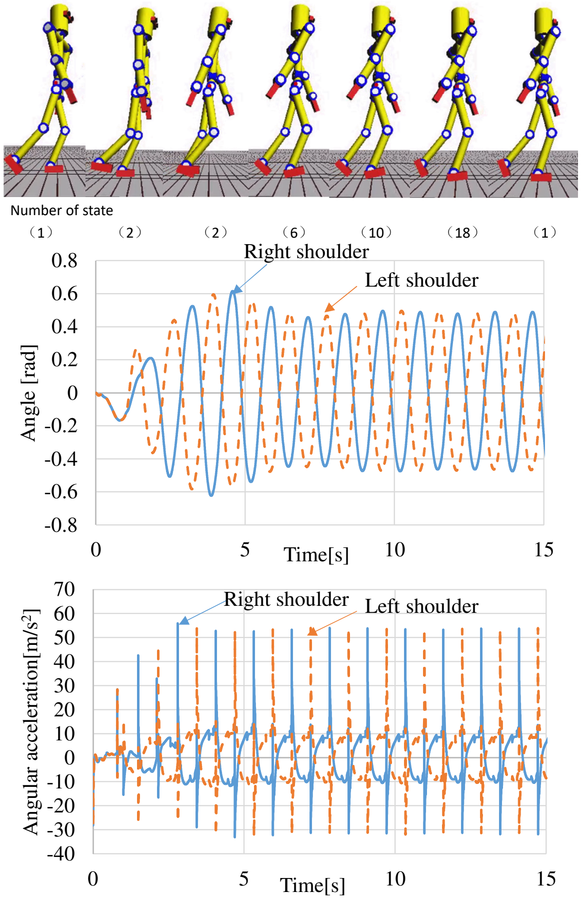

Fig. 4. Screen-shot and the angle/the angular acceleration when input torque in the yaw rotation

4.2.1 without input torque

Firstly, considering the case of no input torque in both yaw rotation of the body ($joint-8$) and the shoulder ($joint-11$ and $joint-14$). We took the joint of the toe ($joint-1$) as an example, as shown in Fig.5. It shows the angular acceleration and the inverse of inertia matrix so that we can see how the toe affect the acceleration of the shoulder joint. Since the numerical value of $M^{-1}_{14,i}$ and $M^{-1}_{11,i}$ of the lower limb portion is always the same(③and④), when calculating $\ddot{q}_{11}$ and $\ddot{q}_{14}$, the lower body contributes the same value to the acceleration calculation of the left and right shoulders(①and②).

Secondly, considering the waist, we took the joint of the yaw rotation of the body ($joint-8$) as an example, as shown in Fig.6. It shows that $M^{-1}_{14,8}$ and $M^{-1}_{11,8}$ are always opposite(③and④). However, τ_i and b_8 are almost zero when there is no input in the yaw angle, so the terms of the waist were the same when calculating $\ddot{q}_{11}$ and $\ddot{q}_{14}$(①and②).

Thirdly, when we considered the upper limb, we took the joint of the right shoulder of the body ($joint-11$) as an example, as shown in Fig.7. The link is branched by the shoulder joint, so the value on one side is always zero(④).

Since this is a symmetrical model, $\sum_{i=11}^{17} M^{-1}_{11,i}(\tau_i - b_i)$ and $\sum_{i=11}^{17} M^{-1}_{14,i}(\tau_i - b_i)$ had become equal. By adding the numerical values of the three parts and the head, the angular acceleration of the left and right shoulder joints became equal, so synchronous arm swing appeared.

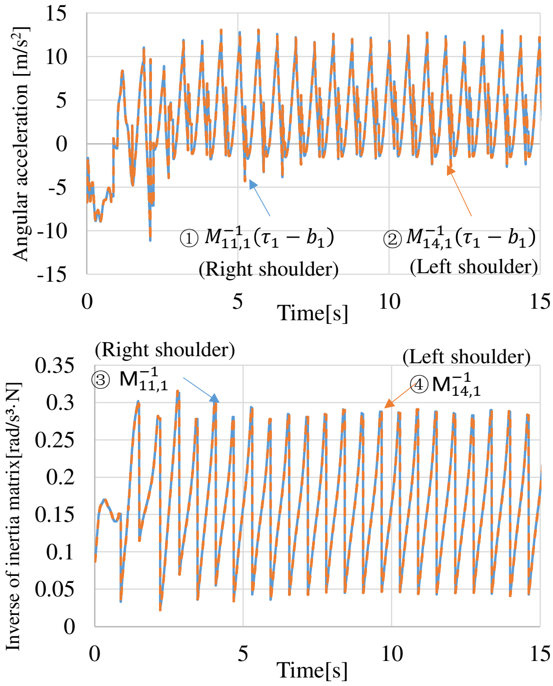

Fig. 5. The angular acceleration/the inverse of inertia matrix (the joint of the toe)

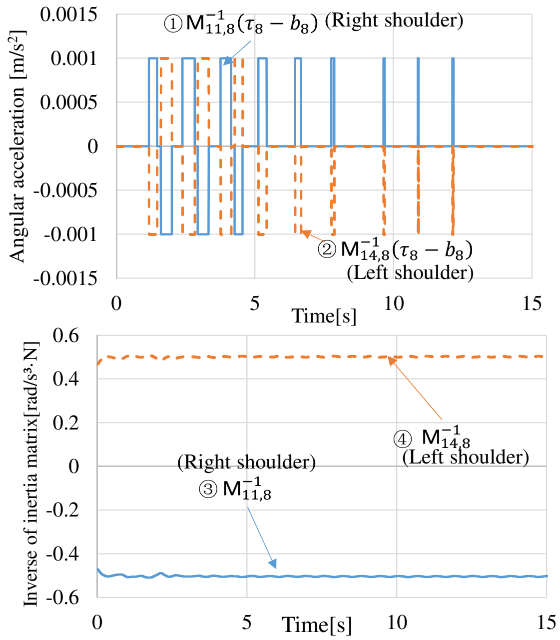

Fig. 6. The angular acceleration/the inverse of inertia matrix (the yaw rotation of the body)

4.2.2 with input torque

This part considered the case that input torque added to the yaw rotation of the body. Firstly, we took the same joint of the toe ($joint-1$) as an example, as shown in Fig.8. As the posture changed, all the $M^{-1}_{14,i}$ and $M^{-1}_{11,i}$ numerical values for the lower limbs changed(③and④). And $M^{-1}_{14,i}$ and $M^{-1}_{11,i}$ have a phase-shifted by π (①and②). When calculating $\ddot{q}_{11}$ and $\ddot{q}_{14}$, the legs $\sum_{i=11}^{17} M^{-1}_{11,i}(\tau_i - b_i)$ and $\sum_{i=11}^{17} M^{-1}_{14,i}(\tau_i - b_i)$ in the lower limbs were out of phase by π, but the sum was almost the same because the model was symmetric, as shown in Fig.9.

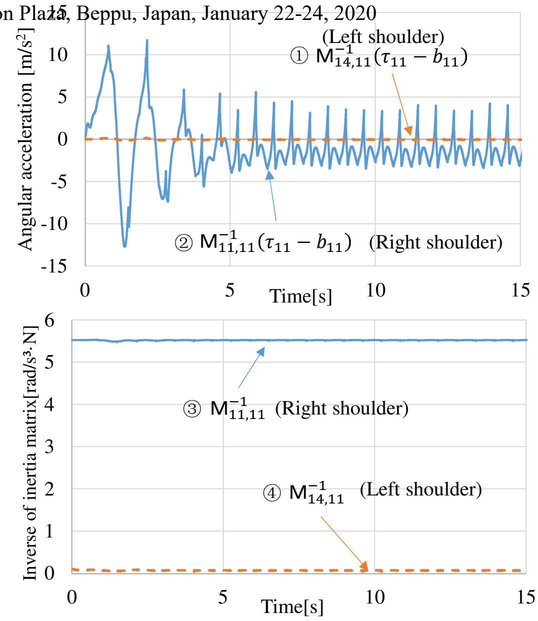

Fig. 7. The angular acceleration/the inverse of inertia matrix (the right shoulder)

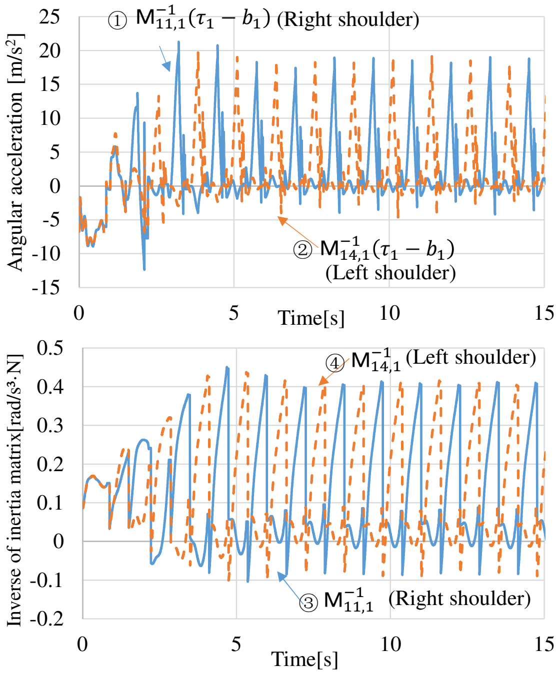

Fig. 8. The angular acceleration/the inverse of inertia matrix (the joint of the toe)

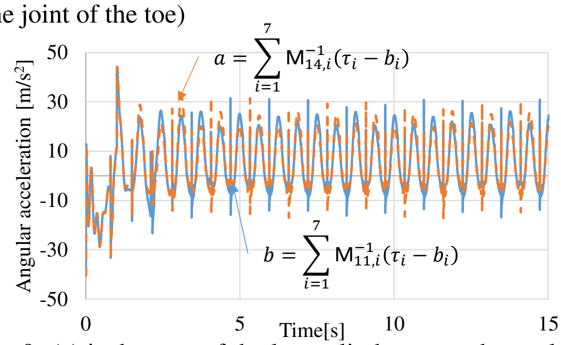

Fig. 9. (a) is the sum of the lower-limb terms when calculating $\ddot{q}_{14}$; (b) is the sum of the lower-limb terms when calculating $\ddot{q}_{11}$

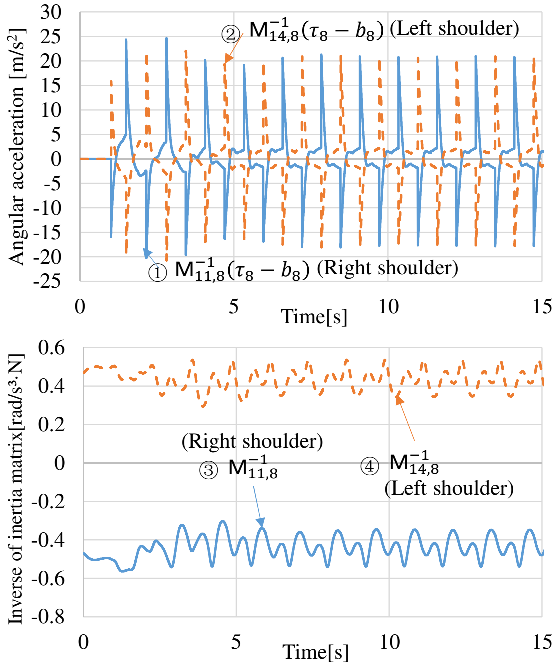

Fig. 10. The angular acceleration/the inverse of inertia matrix (the yaw rotation of the body)

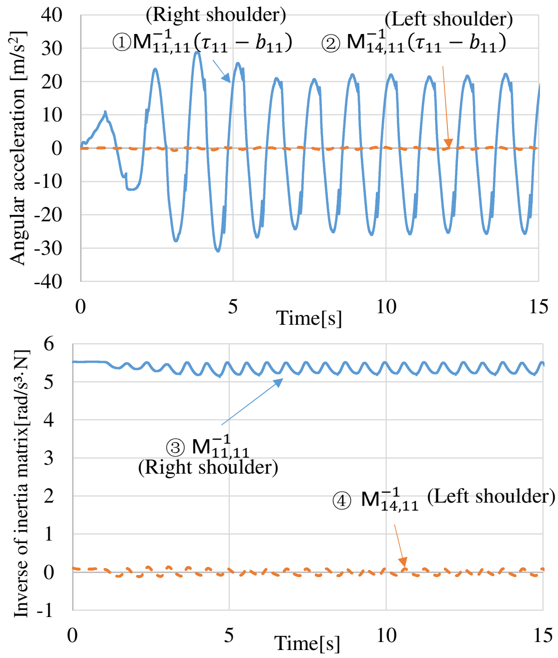

Fig. 11. The angular acceleration/the inverse of inertia matrix (the right shoulder)

Then, as for the waist, we took the same joint of the yaw rotation of the body ($joint-8$) as an example. $M^{-1}_{14,8}$ and $M^{-1}_{11,8}$ are almost opposite(③and④), as shown in Fig.10. The terms for calculating the angular acceleration of the left and right shoulder joints by $\tau_i - b_i$ are symmetric(①and②).

After that, we took the joint of the right shoulder of the body ($joint-11$) as an example when considering the upper limb, as shown in Fig.11. Compared with Fig.7, due to the dynamic coupling, b_i , which is the sum of the centrifugal force/Coriolis force term, the gravity term and the friction force term of the $joint-11$ became larger than the situation that without input torque (①and②).

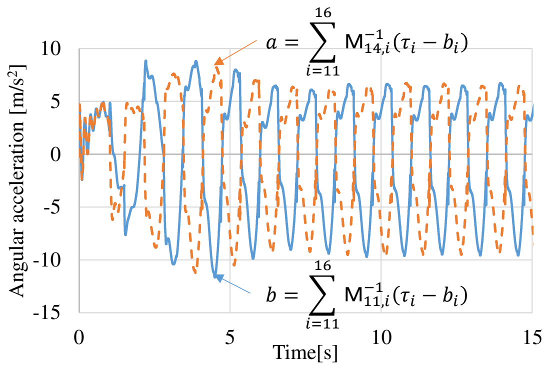

Fig. 12. (a) is the sum of the upper-limb terms when calculating $\ddot{q}_{14}$; (b) is the sum of the upper-limb terms when calculating $\ddot{q}_{11}$

When calculating the sums of the upper limb terms, $\sum_{i=1}^{17} M_{11,i}^{-1}(\tau_i - b_i)$ and $\sum_{i=11}^{17} M_{14,i}^{-1}(\tau_i - b_i)$ became the opposite, as shown in Fig.12.

Overall, by adding the three parts and the head term, since the terms of the yaw rotation of the body and the upper limb had contributed almost the opposite value to the acceleration calculation of the left and right shoulders, the symmetrical arm swing appeared.

According to the above data, we can conclude that when the shoulder joint without input torque, the natural arm swing is directly related to the input torque in the yaw rotation of the body when bipedal walking. To be more specific, the reason why the natural arm swing is symmetrical opposite is that the toque in the yaw rotation of the torso has different dynamic coupling on the left and right shoulder joints.

5 CONCLUSION

In this paper, we introduced a rigorous physical humanoid model and simulated arm-swing with/without an input torque in yaw rotation of the torso. According to the results of the simulation, we have made a hypothesis that vibration in the yaw rotation of the torso might be the reason to cause natural arm swing. Then we proved it and introduced how the yaw rotation of torso influences arm-swing through the dynamic coupling by Newton-Euler Method.

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