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Practical Experiment of Balancing for a Hopping Humanoid Biped against Various Disturbances

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Abstract— **This paper discusses balancing for a hopping humanoid biped against various disturbances. Contrary to other studies, the present work focuses on the practical experiment with a real humanoid biped, HUBO2. Also, hopping is focused on among various types of locomotion since hopping is simple movement but more dynamic rather than walking. Two control strategies are proposed according to the magnitude of the disturbances. The one is the posture balance control for small disturbance, which uses the ankle torque of the stance leg. The other is to use the posture balancing control and the landing position control together for large disturbance. The landing position controller changes the landing position of the swing foot to maintain stability. The closed form solution of the landing position controller is addressed with the simplified model. As this simplification, both controllers are used together since the landing position controller cannot maintain a perfect balance alone. To this end, practical experiments with HUBO2 are conducted. In the experiments, HUBO2 maintains a balance against not only small disturbance but also large disturbance such as pushing through the proposed control strategies.**

I. INTRODUCTION

There is no doubt that a robot will hold a dominant position in the human's future life. With intelligent abilities such as manipulation, mobility, navigation, recognition and human-robot interaction, the future robot will provide service to human beings in houses or companies, improving the quality of their life. The humanoid biped is also the one of them. Even though the humanoid biped will usually walk, it will have to run or hop at the specific situation such as avoiding obstacles or faster movement. Therefore, many researchers are studying on not only walking but also running or hopping. Honda's ASIMO [1], Toyota's Partner robot [2], KAIST's HUBO2 [3], Sony's QRIO [4], and so on are being studied for hopping or running of the humanoid biped.

If robots and human beings live together, the robots can lose the stability due to unexpected disturbance such as pushing by human. The stabilization method for disturbance of the humanoid biped can be classified into three strategies, which are ankle torque strategy, reactive momentum strategy, and foot placement strategy [5][6] (Figure 1). The ankle torque strategy is to control for the zero momentum point (ZMP) to be maintained within the supporting polygon using an additional torque of ankle actuator of a stance leg, when the disturbance is applied to the humanoid biped. If the disturbance is grown, it is impossible to maintain stability with only the ankle torque. At this case, the reactive momentum generated by movement of torso or arm is used to hold the ZMP within the supporting polygon. However, even the reactive momentum is impossible to balance if the disturbance is bigger and bigger. At this case, the foot placement strategy, changing the landing position of the swing foot, is used. This method can be imagined by intuition.

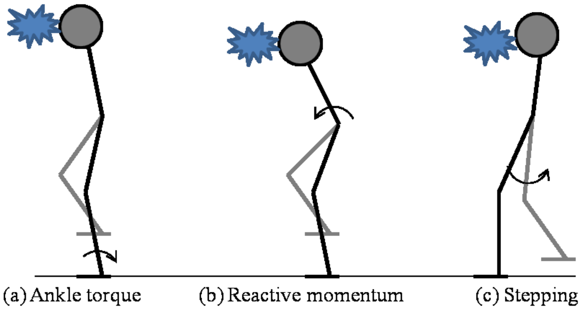

Figure 1. Balancing strategies for various disturbances

In 2009, R. Tajima showed the demonstration which Toyota's Partner robot maintains a balance against disturbance with stepping strategy [2]. However, there is no mention of the foot placement algorithm. Also, J. Pratt [7] calculated a capture region with a linear inverted pendulum model attached a flywheel, and verified it with a simulation of a simple model. A. Kuo [5] used a change of a foot placement for passive dynamic walking. And, M. Raibert [8] developed 3d biped being able to hop and run. Like as these studies, the foot placement strategy is being studied so many, but the realization with the real humanoid biped has not been announced yet except for the Toyota's Partner robot. Even though the outstanding method is proposed theoretically and is verified by the simulation, it is

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difficult to realize the proposed method with the real robot.

Therefore, this paper focuses on how to maintain a balance against the disturbance and its realization with the real humanoid biped while the robot hops in place. The hopping pattern is generated by the pattern generation method proposed in the previous paper [9]. Different methods are proposed to maintain a balance according to the magnitude of the disturbance, and those are realized by the real humanoid biped, HUBO2.

The proposed methods are classified into two ways. The first is the posture balance control, which use the ankle torque of the stance leg. It can maintain a balance of the robot against small disturbance. On the other hand, if the disturbance becomes bigger, the first way is switched to the second one, which is based on the landing position control, the change of the foot placement of the swing foot. This switching is decided by the estimated ZMP using a signal of an inertia measurement unit (IMU).

However, it is almost impossible to get the closed form solution of the landing position of the swing foot against the disturbance. To use the closed form solution, simplified model is used. The humanoid biped has been simplified to various models. S. Kajita [10] introduced a linear inverted pendulum model, and J. Pratt [7] used a more advanced one, a linear inverted pendulum model having flywheel. However, they assumed that there is no loss of energy when the leg is switched. That is, the impact model was not used. Also, T. Komura [11] used an angular momentum pendulum model. In this paper, a single inverted pendulum model is used, which is composed of a single mass and mass-less legs. And, the impact model is introduced because the impact seriously affects the dynamics of hopping. Even though the closed form solution is get, it cannot control the real robot. Therefore, the posture balance control is used together with the landing position control in the second way.

This paper is organized as follows: Section 2 explains the overall strategy for various disturbances while the robot hops. Section 3 provides details of the posture balance control for small disturbance, and the landing position control for large disturbance is addressed in Section 4. Finally, the last section concludes the paper.

II. OVERALL STRATEGY OF BALANCING FOR VARIOUS DISTURBANCES

The basic principle for humanoid biped to handle disturbance is the same or similar even if the robot walks, runs or hops. However, this paper addresses how to maintain a balance when the humanoid biped hops in place. To make a balance for various disturbances, we introduce two strategies. The one is the posture balance control using the ankle torque of the stance leg, and the other is the combination of the posture balance control and the landing position control, which changes the landing position of the swing foot.

For small disturbance, the posture balance control maintains a stability of the robot. It works with the inertia measurement unit (IMU) sensor in the main computer every 5 milliseconds. Otherwise, if disturbance is larger, the robot cannot maintain a balance with only the posture balance controller. At this time, the landing position controller is used together with the posture balance controller. If the ZMP, estimated by the signal of the IMU sensor, is located within the sole of the stance foot, the posture balance controller works only. On the other hand, if it is not, the landing position controller is activated in addition. The activation of the landing position control is decided just before when to start one step hopping, every 330 milliseconds which is the step time of HUBO2. If the landing position controller is switched on, the landing position of the swing foot is calculated. Then, the reference trajectories of all the joints are recalculated according to the changed foot placement by the hopping pattern generation method. Finally, the robot can make continuous hopping stably with the change of the landing position of the swing foot.

III. BALANCING FOR SMALL DISTURBANCE

Small disturbance for the humanoid robot is generated by an inclination of the ground, slight touch of the robot, and so on. The compliance due to a geometrical structure of the robot, reducer, rubber bush of the sole, compliant F/T sensor and harmonic drive gear can be vibrated by the small disturbance. And, the robot can fall down. The posture balance controller is introduced to prevent the effect of the small disturbance. This controller can be applied to not only hopping of the robot but also running. This controller is the same as the controller used for running forward in the previous work [3].

A. Summary of the posture balance control

Since the posture balance control was described well in the previous work [3], it is addressed briefly here. The humanoid biped is simplified as the inverted pendulum having a point mass, spring and damper in Figure 2. The transfer function is as follow.

$$TF \equiv \frac{\frac{K}{mL^2}}{s^2 + 2\varsigma\omega_n s + \omega_n^2} \tag{1}$$

The parameters in the equation (1) are estimated with the system identification.

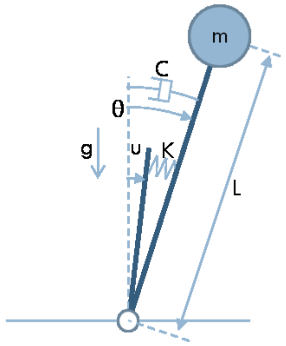

Figure 2. The simplified model

Moreover, the control law is as follow.

$$\begin{aligned} u_{AnklePitch} &= \theta_{AnklePitch}^{Ref} + \theta_{AnklePitch}^{Control} \\ &= \theta_{AnklePitch}^{Ref} + C_{Filter} K_P (\theta_{AnklePitch}^{Ref} - \theta_{AnklePitch}^{IMU}) \end{aligned} \quad (2)$$

$\theta_{AnklePitch}^{Ref}$ means the pre-scheduled ankle trajectory in the hopping pattern generation, $\theta_{AnklePitch}^{Control}$ means the control input created by the posture balance controller. The posture balance controller uses a P-controller. The structure of the posture balance controller in the sagittal plane is shown in Figure 3.

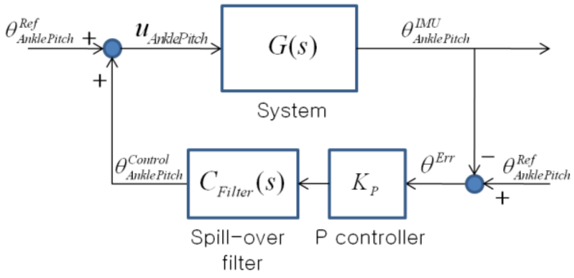

Figure 3. Block diagram of the posture balance controller in the sagittal plane

B. Experiment

The proposed controllers were applied to the humanoid robot, HUBO2 when small disturbance is applied. Figure 8 is snap shots of the balancing experiment for small disturbance when the HUBO2 hops in place. As shown in the third picture of third row of Figure 8, HUBO2 was pushed slightly. However, the robot maintained the stability through the posture balance control, not the landing position control. It is worthy of attention that the robot doesn't change the foot placement of the swing foot. It will be explained in next section.

IV. BALANCING FOR LARGE DISTURBANCE

When the humanoid robot hops in place or runs forward, it can maintain stability with the posture balance controller against small disturbance. However, when a large disturbance such as pushing is applied, the robot cannot maintain stability with only the posture balance controller, since the ZMP escapes the support polygon, the sole. So, in the case of a large disturbance, the landing position controller is used to maintain balance of the humanoid robot. The landing position controller changes the landing position of the swing foot to the capture point [7]. In other words, the landing position controller is only used when the ZMP is escaped the support sole.

Since the dynamics of the humanoid robot is complicated, it is difficult to get a closed form solution of the capture point for general humanoid robot. To get the closed form solution, the humanoid robot is simplified. Moreover, the impact model is introduced to calculate the solution since it seriously affects the dynamics after landing.

However, since the simple model and general humanoid robot make different dynamics, the real humanoid robot cannot make the stability perfectly with the capture point calculated by the simple model. To cover this difference between simple model and real one, the posture balance control in the previous section is used together with the landing position control. That is, large disturbance is reduced with the landing position controller to small one, and then remained small disturbance is eliminated by the posture balance controller.

A. System Simplification

To design the landing position controller, the humanoid robot is simplified as an inverted pendulum having two legs, as illustrated in Figure 4. Some assumptions are employed. m is the total mass of the robot and it is concentrated on a point. Both legs have no mass or inertia, and the length of the legs is fixed since their movement is relatively smaller than the length of the leg. θ_1 denotes the angle of the stance leg with respect to vertical, and α is the angle between both legs. Also, since the flight time is short, the effect of rotation of the robot during the flight phase is negligible. Thus, it is assumed that the robot always contacts the ground. Finally, it is further assumed that the sole of the robot does not exist, the foot of the robot contacts the ground with a point, and there is no slip. The range of α is set as follows.

$$0^\circ \le \alpha \le 90^\circ \quad (3)$$

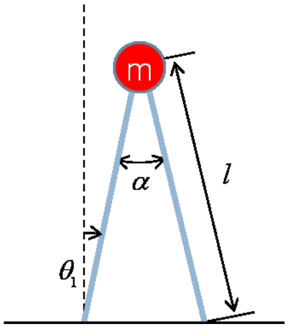

Figure 4. Simplified Model for the landing position control

On the other hand, we have to know where ZMP is to apply the landing position controller. It is reason that the landing position controller is activated only when ZMP is escaped the support sole. The ZMP equation of the simple model is as follows. θ_1 is estimated with the IMU sensor

$$ZMP = \frac{l^2\ddot{\theta}_1 + gl\sin\theta_1}{-l\cos\theta_1\dot{\theta}_1^2 - l\sin\theta_1\ddot{\theta}_1 + g} \tag{4}$$

In HUBO2, the lengths from the ankle joint to the toe and heel are 140mm and 80mm. Therefore, if the ZMP is escaped from -80 mm to 140 mm, the switch for the landing position controller turns on. However, we set the margin as 30 mm to prevent the unexpected situation in the real environment. Finally, the criterion for the landing position controller is set as follow.

$$\textit{Switch of the landing position controller} = \begin{cases} off(-50mm \le ZMP \le 110mm) \\ on(ZMP < -50mm, ZMP > 110mm) \end{cases} \tag{5}$$

B. How to find the angle between both legs, a capture point

Figure 5 shows the procedure of the landing position control. The key issue of this controller is where to take a step of the swing foot. That is, it is the strategy of this controller that the humanoid robot maintains a perfect balance ((c) of Figure 5) with the single stepping ((b) of Figure 5) when the humanoid robot is applied disturbance ((a) of Figure 5). The landing position can be substituted with the angle between both legs, α.

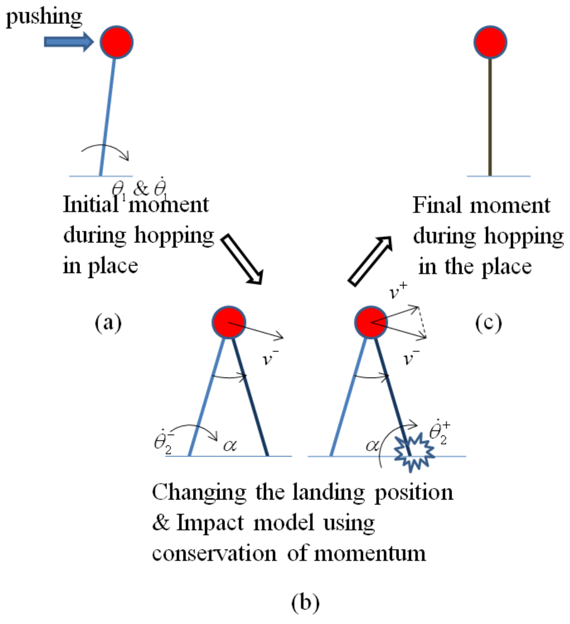

Figure 5. Procedure of the landing position control

To find α, the principles of energy conservation and angular momentum conservation are used. The energy is conserved from the start of hopping to just before impact. This is expressed as given below.

$$E_1 = \frac{1}{2}ml^2\dot{\theta}_1^2 + mgl\cos\theta_1 \tag{6}$$

$$E_2^- = \frac{1}{2}ml^2\left(\dot{\theta}_2^-\right)^2 + mgl\cos\frac{\alpha}{2} \tag{7}$$

$$\therefore \frac{1}{2}ml^2\dot{\theta}_1^2 + mgl\cos\theta_1 = \frac{1}{2}ml^2\left(\dot{\theta}_2^-\right)^2 + mgl\cos\frac{\alpha}{2} \tag{8}$$

E_1 is the initial energy when the robot starts to hop ((a) of Figure 5), and E_2^- is the energy just before the robot lands (left of (b) of Figure 5). θ_1 and $\dot{\theta}_1$ are the angle and the angular velocity of the stance leg when the robot start to hop, and $\dot{\theta}_2^-$ is the angular velocity of the stance leg just before the robot lands.

After landing, the swing foot contacts the ground and the robot rotates. Upon landing, the angular velocity is changed by the impact. The equation is expressed by the conservation of angular momentum as given below.

$$v^- = l\dot{\theta}_2^-$$

$$v^+ = v^-\cos\alpha = l\dot{\theta}_2^-\cos\alpha = l\dot{\theta}_2^+$$

$$\therefore \dot{\theta}_2^+ = \dot{\theta}_2^-\cos\alpha \tag{9}$$

As shown in (b) of Figure 5, v^- is the linear velocity of the COM just before impact and v^+ is the linear velocity of the COM just after impact. $\dot{\theta}_2^+$ is the angular velocity of the stance leg just after impact.

After impact, the energy of the robot is conserved again. If α is proper, the robot will hop in place well without falling down as shown in (c) of Figure 5. It can be expressed as following energy conservation equation.

$$\frac{1}{2}ml^2\left(\dot{\theta}_2^+\right)^2 + mgl\cos\frac{\alpha}{2} = mgl \tag{10}$$

Therefore, α, which makes the humanoid robot applied a large disturbance hop stably, is calculated by equations (8), (9) and (10). Equation (9) is substituted for equation (10) as below.

$$\frac{1}{2}ml^2\left(\dot{\theta}_2^-\right)^2\cos^2\alpha = mgl\left(1-\cos\frac{\alpha}{2}\right) \tag{11}$$

And, the following replacement is used to expand the equation simply.

$$t = \cos\frac{\alpha}{2}$$

With the equation (3), the range of t is as below.

$$\frac{1}{\sqrt{2}} \le t = \cos\frac{\alpha}{2} \le 1$$

Also,

$$\cos\alpha = 2\cos^2\frac{\alpha}{2} - 1 = 2t^2 - 1$$

Equations (8) and (11) are expressed with t and E_1 as below.

$$\frac{1}{2}ml^2\left(\dot{\theta}_2^-\right)^2 = E_1 - mglt \qquad (12)$$

$$\frac{1}{2}ml^2\left(\dot{\theta}_2^-\right)^2(2t^2-1)^2 = mgl(1-t) \qquad (13)$$

Equation (13) is substituted by equations (6) and (12) as below.

$$(E_1 - mglt)(2t^2-1)^2 = mgl(1-t) \qquad (14)$$

Therefore, α is calculated by solving equation (14).

Equation (14) is changed as below.

$$E_1 = \frac{mgl(1-t)}{(2t^2-1)^2} + mglt \qquad (15)$$

If the left side and the right side of equation (15) are identical, a solution exists. To verify the existence of the solution, both sides of equation (15) are compared.

In the previous simplified model (Figure 5), if the robot hops in place stably, the initial energy of the robot ((a) of Figure 5), E_1, becomes as given below.

$$E_1 = mgl \qquad (16)$$

If the robot is pushed, the initial energy of the robot increases because the pushing adds energy. That is,

$$E_1 = \frac{1}{2}ml^2\dot{\theta}_1^2 + mgl\cos\theta_1 > mgl \qquad (17)$$

The stronger the robot is pushed, the larger E_1 becomes. Therefore, the initial energy of the robot theoretically has the following range.

$$mgl \le E_1 < \infty$$

Otherwise, the right side of equation (15), f_{fight}, is given as follows.

$$f_{fight}(t) = \frac{mgl(1-t)}{(2t^2-1)^2} + mglt \qquad (18)$$

We can know the range of f_{fight} with substituting t by $\frac{1}{\sqrt{2}}$ and 1, as below.

$$f_{fight}\left(\frac{1}{\sqrt{2}}\right) = \frac{mgl(1-t)}{(2t^2-1)^2} + mglt \to \infty$$

$$f_{fight}(1) = mgl$$

$$\therefore mgl \le f_{fight}(t) < \infty$$

That is, we can make any value of f_{fight} from mgl to ∞ with t from $\frac{1}{\sqrt{2}}$ to 1. Therefore, since both sides of equation (15) have the same range, a solution exists.

To calculate the solution easily, equation (15) is linearized as follows when t becomes 1, which means that α is zero.

$$E_1 = \frac{mgl(1-t)}{(2t^2-1)^2} + mglt \approx 8mgl(1-t)^2 + mgl \qquad (19)$$

Finally, the closed form solution, α, is calculated as presented below.

$$\alpha = 2\cos^{-1}\left(1 - \sqrt{\frac{\frac{1}{2}mgl^2\dot{\theta}_1^2 + mgl\cos\theta_1 - mgl}{8mgl}}\right) \qquad (20)$$

C. Experiment

The posture balance controller always works while HUBO2 hops or runs. When the humanoid robot hopping in place is pushed strongly, if the estimated ZMP is escaped the criterion for the landing position control, the landing position controller works together with the posture balance controller. Figure 6 - Figure 9 show the experimental result. Figure 6 shows the estimated ZMP using the IMU sensor and it is escaped the lower boundary (-0.05m) for landing position control mentioned in section 5.1 at 3.925 seconds. Therefore, the landing position controller is activated at that time. Since this controller works every step (0.330 seconds), the landing position of the swing foot is changed for next step (3.960-4.290 seconds) after activating this controller. And, the exchanged foot position is returned to original figure for 4.290-4.620 seconds. Figure 7 shows that the desired trajectories of both hip pitch joints are changed for 3.960-4.620 seconds. Trajectories of other joints are also changed. With this procedure, HUBO2 can hop in place stably against large disturbance. Figure 9 shows snap shots of the experiment. HUBO2 is pushed in the 4th picture and it changes the landing position of the swing foot in the 7th picture. After that, HUBO2 hops well again.

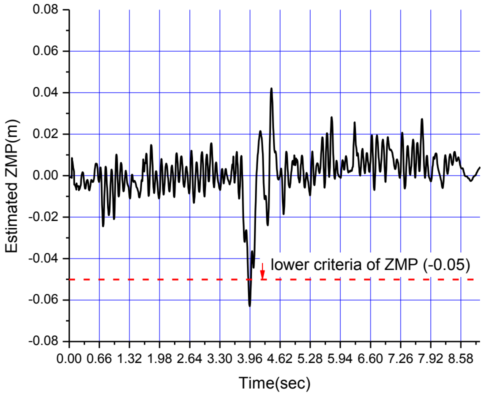

Figure 6. Estimated ZMP of the robot. The estimated ZMP, which is estimated by the IMU signal of Figure 15, is escaped the lower criteria for the landing position controller at 3.925 seconds. Therefore, the landing position controller is activated.

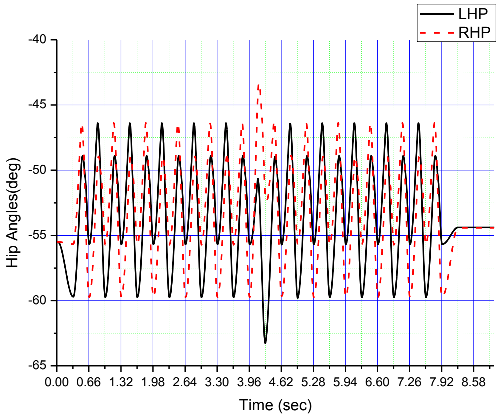

Figure 7. Desired trajectories of both hip pitch joints. LHP denotes a joint of the left hip pitch and RHP is right one. Because the landing position controller is activated at 3.925 seconds, the trajectory for hopping is changed for the next step (3.960-4.290 seconds) after activating the controller.

V. CONCLUSION

In this paper, Balancing for hopping of a humanoid robot was discussed. Specifically, this study focuses on how to maintain balance against various disturbances through practical experiments with a real humanoid robot, HUBO2. Two strategies are proposed to maintain balance according to the magnitude of the disturbance. If small disturbance is applied, the robot can make a balance with the posture balance controller. Otherwise, if large disturbance is applied, the landing position controller and the posture balance controller works together. Even though the landing position is obtained by the simplified model, the usage of those controllers together compensates the difference between the simplified model and the real robot.

That is, the effect of the large disturbance is reduced with the landing position controller, and then, the remained disturbance is controlled by the posture balance controller. In the experiment, HUBO2 maintained its balance well against various disturbances through the proposed control strategies. In the future, with improvement, the humanoid robot will be able to maintain balance against various disturbances while it runs forward.

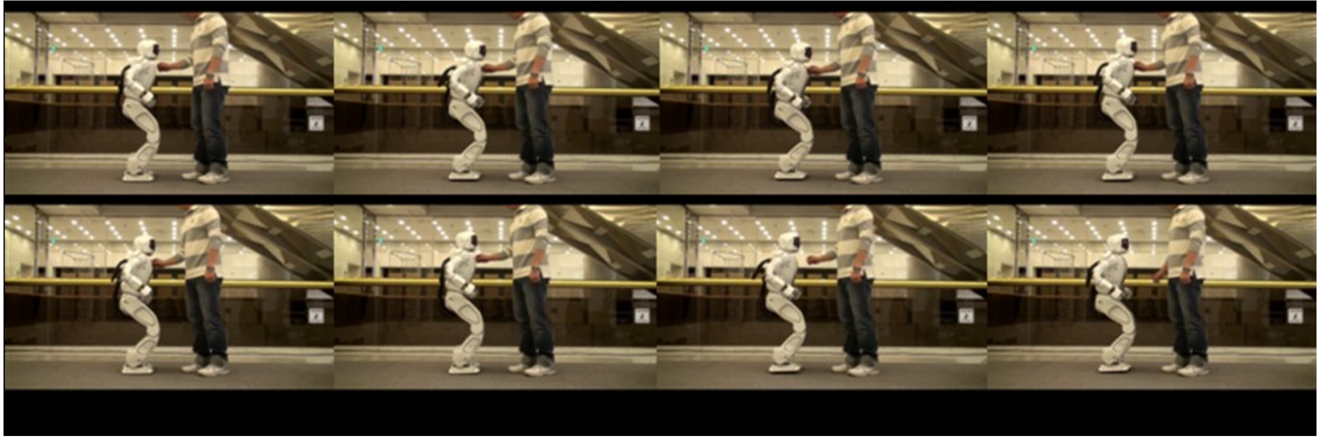

Figure 8. Series of snap shots for balancing with only posture balance controller. After pushing (6th picture), HUBO2 maintains stability with the posture balance control not the landing position control. There is no change of the landing position of the swing foot.

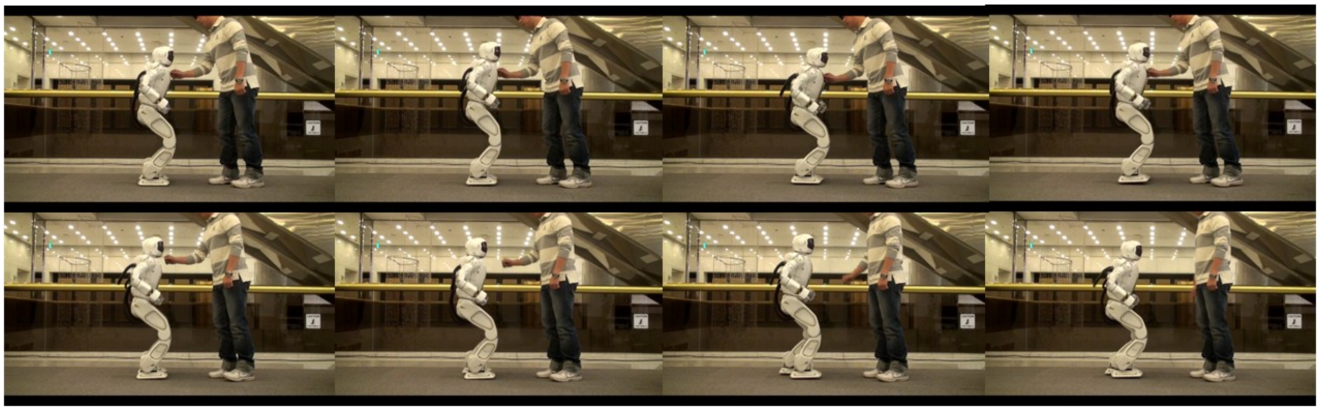

Figure 9. Snap shots for balancing with the landing position control and the posture balance control. After pushing (4th picture), HUBO2 exchanges the landing position of the swing foot (7th picture)

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