Stand Balancing Strategies for a Humanoid Robot with Slidable Floor

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***Abstract*—This paper presents a trajectory generation process of a humanoid robot (HR) to restore its balance from a moving floor. The experiment applies a 1kg iron weight hits to the slidable floor(cart) while a robot is standing on it. The impact produces a 2.97N external force to the cart and thus makes the robot unstable and later falling down. The objective of this work is to determine a balance recovery motion or trajectory, using an inverse kinematics model together with robot's joints control strategies. Two joints control strategies are implemented i.e. ankle and ankle-hip. The performance of the trajectories is demonstrated through the jerk. This can be analyzed via the HR's joint angle profile using the cubic spline technique. These profiles are then applied to the real humanoid robot. The satisfied results are achieved for both strategies. However, the ankle-hip strategy gives a shorter recovery period than the ankle strategy.**

***Index Terms*—humanoid robot, inverse kinematics, cubic spline, forward kinematics, stand balancing slidable floor.**

I. Introduction

Humanoid robot research has extensively been investigated over the past two decades. Various research aspects are explored such as a localization method navigate HR in muti-level indoor environments [1], a walking control HR on uneven terrain [2], and a falling recovery of the HR[3-5]. This work focuses on the falling recovery issue.

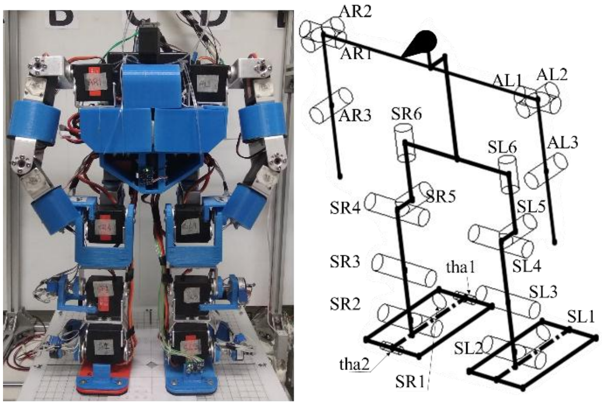
There are three popular strategies for a balance recovery from external force. The strategies are moving ankle or/and hip joints and taking foot step.

The ankle and hip joints control strategies shown in [3] is a push recovery of the HOAP-2 humanoid robot from continuous disturbance. They employ the ZMP in the dynamics model to determine a desired trajectory.

A human size Sarcos humanoid robot[4] is pushed from behind and it takes a foot step to restore its balance. The PKU-HR5 humanoid robot[5] exploits all three strategies to keep its balance when a sudden force is applied. The HOAP-2[6] is also pushed horizontally at the foot with a 1.7N external force. The robot uses hip strategy with a dynamics method to recovery the balance in 2.4sec.

As this research focuses on using ankle and ankle-hip strategies to restore robot's balance from the slidable cart, the center of gravity (CoG) of a robot is analyzed and manipulated to determine desired trajectory. The CoG is a result of the robot kinematics model. The cubic spline function is applied to find a jerk of each joint. The jerk helps to show the trajectory performance.

This paper is organized into five parts, starting with the introduction in the first part follows by the robot hardware and methodology as the second part. The experimental design is demonstrated in the third section. Section four explains the result of each strategies that applied to the real HR and conclusion is in the Section five.



a) b)

Figure 1. Structure of the eeKKU-II humanoid robot, a) an actual robot and b) joints defining.

II. Robot Hardware and Methodology

A. Humanoid Robot

The eeKKU-II, Fig. 1-a), is a small and low-cost humanoid platform developed from the eeKKU-I. Its weight is 2.94kg and 42cm tall. It is constructed from aluminum and ABS filament. The robot has 18 degree of freedoms (DOFs), 6DOFs of each leg and 3DOFs of each arm. The controller board is 16bits microcontroller, Arduino MEGA2560, together with a computer via USB port. Actuator is servo motor with high torque of 35kg-cm. The Arduino board performs as a local control while a computer is acquired joint angle data. Fig. 1-b) presents the robot joints and its links.

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B. *Forward Kinematics*

The work uses a forward kinematics (FK) by Denavit-Hartenberg convention (DH) to determine the total CoG of HR, as shown in (1).

$$(X,Y,Z)=F(\theta) \tag{1}$$

FK analysis explains orientation and translation of frame joint from a reference frame until an end-effector frame by transformation matrices (T) [7], as in (2). The CoG can be considered as an end-effector.

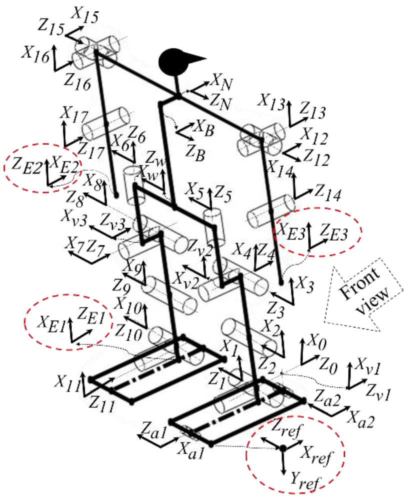

Figure 2. Coordinate frame of the eeKKU-II.

$$^{i-1}T_i=\begin{bmatrix} C(\theta_i) & -S(\theta_i)C(\alpha_i) & S(\theta_i)S(\alpha_i) & a_iC(\theta_i) \\ S(\theta_i) & C(\theta_i)S(\alpha_i) & -C(\theta_i)S(\alpha_i) & a_iS(\theta_i) \\ 0 & S(\alpha_i) & C(\alpha_i) & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2}$$

Parameter C and S represent cos( ) and sin( ) function. Subscript i identifies robot frame order of a robot. Parameter d, a, and α are an offset link, a link length, and an offset angle, respectively. Fig. 2 shows coordinates frame of all the eeKKU-II's joint. Since a humanoid robot is a complex serial robot type, the robot model is thus split into 3 linkages. The transformation matrices of these are shown in (3) to (6)

$$^{ref}T_{E1}= {}^{ref}T_w\, {}^{w}T_6\, {}^{6}T_{v3}\, {}^{v3}T_7\, {}^{7}T_8\, {}^{8}T_9\, {}^{9}T_{10}\, {}^{10}T_{11}\, {}^{11}T_{E1} \tag{3}$$

$$^{ref}T_{E2} = {}^{ref}T_w\, {}^{w}T_B\, {}^{B}T_N\, {}^{N}T_{15}\, {}^{15}T_{16}\, {}^{16}T_{17}\, {}^{17}T_{E2} \tag{4}$$

$$^{ref}T_{E3} = {}^{ref}T_w\, {}^{w}T_B\, {}^{B}T_N\, {}^{N}T_{12}\, {}^{12}T_{13}\, {}^{13}T_{14}\, {}^{14}T_{E3} \tag{5}$$

$$^{ref}T_w = {}^{ref}T_{a1}\, {}^{a1}T_{a2}\, {}^{a2}T_{v1}\, {}^{v1}T_0\, {}^{0}T_1\, {}^{1}T_2\, {}^{2}T_3\, {}^{3}T_4\, {}^{4}T_{v2}\, {}^{v2}T_5\, {}^{5}T_w \tag{6}$$

All parameter of a right leg is illustrated in Fig. 3-a). A simple model of coordinate frame for the CoG are determined as in (7).

$$^{ref}T_{COG} = {}^{ref}T_{a1}\, {}^{a1}T_{a2}\, {}^{a2}T_v\, {}^{v}T_1\, {}^{1}T_2\, {}^{2}T_3\, {}^{3}T_{COG} \tag{7}$$

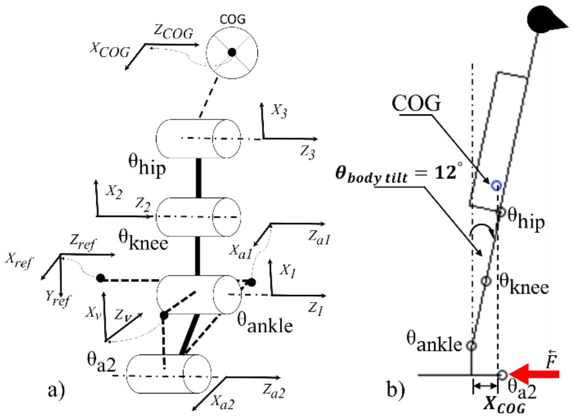

Figure 3. a) co-ordinate frame of the CoG, and b) body tilt angle.

Angle θ_{a2} in Fig. 3 is a virtual joint represents an angle between robot toe and the floor. This angle is occurred when the cart is hit, and the humanoid robot is tipped to the front. The robot feet are not fixed to the cart.

C. *Inverse Kinematics Solution for the CoG*

The Inverse Kinematics (IK) is utilized to determine all joint angles while an end-effector (CoG position) is known. The damped least squares technique is employed to solve the IK problem, as shown in Fig. 4.

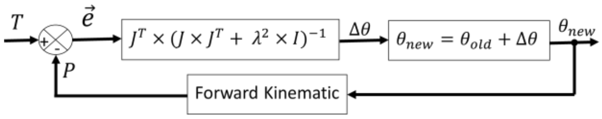

Figure 4. IK by damped least squares method [8].

The damped least squares technique [8] has advantages of using a small number of iterations. The relationship between a linear velocity ($\vec{e}=T-P$) with angular velocity ($\Delta\theta$) of the end-effector is $\vec{e}=J\Delta\theta$, while J is a Jacobean matrix. In this work, J is not a square matrix and it is nearly singular when the model HR is home position.

D. *Cubic Spline Interpolation*

In order to analyze the jerk of joint angle, the trajectory function $Q(t)$ is required. To fit smooth curve $Q(t)$ as in (8), the cubic spline method is used.

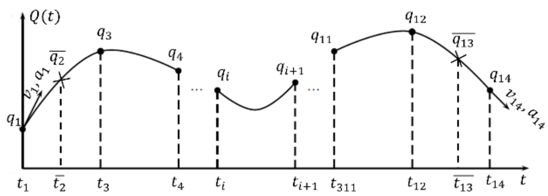

Figure 5. Cubic spline interpolation [9].

In this work, the trajectory profile is split into small curves, $q(t)$, as shown in Fig. 5. It consists of 12 knots and 2 extra knots ($\bar{q}_2$, $\bar{q}_{13}$) are needed in order to determine initial and final velocities and acceleration (v_1, v_{14}, a_1, a_{14}), which are set to zero. As in (9), q_i is interpolation function, j is number of joint robots, i is a knot, $\ddot{q}_{j,i}$ is the acceleration at the knot and h_i is difference between $t_{i+1} - t_i$.

$$Q(t) \begin{cases} q_1(t)\ ;\ t_1 \le t \le \bar{t}_2 \\ q_2(t)\ ;\ t_2 \le t \le t_3 \\ \vdots \\ q_{14}(t)\ ;\ \bar{t}_{13} \le t \le t_{14} \end{cases} \tag{8}$$

$$\begin{aligned} q_{j,i} = {} & \frac{\ddot{q}_{j,i}(t_i)}{6h_i}(t_{i+1}-t)^3 + \frac{\ddot{q}_{j,i}(t_{i+1})}{6h_i}(t-t_i)^3 \\ & + \left(\frac{q_{j,i}}{h_i} - \frac{h_i \ddot{q}_{j,i}(t_i)}{6h_i}\right)(t_{i+1}-t) \\ & + \left(\frac{q_{j,i+1}}{h_i} - \frac{h_i \ddot{q}_{j,i}(t_{i+1})}{6h_i}\right)(t-t_i) \end{aligned} \tag{9}$$

Equation (10) is a jerk of each interval time (t_i). It is the third derivatives of (9). The equation is utilized to obtain jerk [10] values of the HR's joint.

$$\dddot{q}_{j,i}(t) = \frac{\ddot{q}_{j,i+1} - \ddot{q}_{j,i}}{h_i} \tag{10}$$

III. Experimental Design

This section describes a hardware setup of this experiment and the joints control strategies utilized to restore robot's balance from a slidable floor.

A. Experimental Setup

Fig. 6 shows an experimental environment hardware where the eeKKU-II standing on a slidable cart, $30x30cm^2$. It can slide horizontally 50cm in X-axis.

The external force is generated from a 1kg iron weight tighten to a 38cm cable. The weight is pulled up to 32deg and let if freely fall to generate a 2.97N force. The impact is made to the cart (seen in Fig. 6). There is a load cell tare in x-axis. Joint angles are acquired from a linear potentiometer sensor. In order to determine tilt angle, a 3-axis gyro and 3-axis acceleration, IMU6050 module, is used.

B. Joints Control Strategies

Two strategies of robot movements are applied which are an ankle joint control strategy and the other is an ankle-hip strategy.

An ankle joint strategy is to control only ankle joint both left and right leg represented by SL2 and SR2, respectively. For an ankle-hip strategy, there are 4 controlled joints; SL2, SR2, left hip (SL4), and right hip (SR4). During experiments, other controlled joints are set to 0deg.

C. Experimentation Procedure

The experiments are divided into 2 parts: a simulation and an actual implementation. The simulation part is the apply the joint angle obtained from the IK and feed to the model aiming to manipulate the CoG to the initial x-y position. The robot reaction period is activated using tilts sensor at 3deg. This is to make sure that the cart is hit. It also causes a delay to robot reaction.

The actual implementation part is an experiment on the real robot. The joint angles achieved from the simulation part are applied to the robot. Raw data from controlled joints are treaded, using the third polynomial regression and the cubic spline techniques, and then analyzed. Finally, an adjustment is made to achieve balance recovery path.

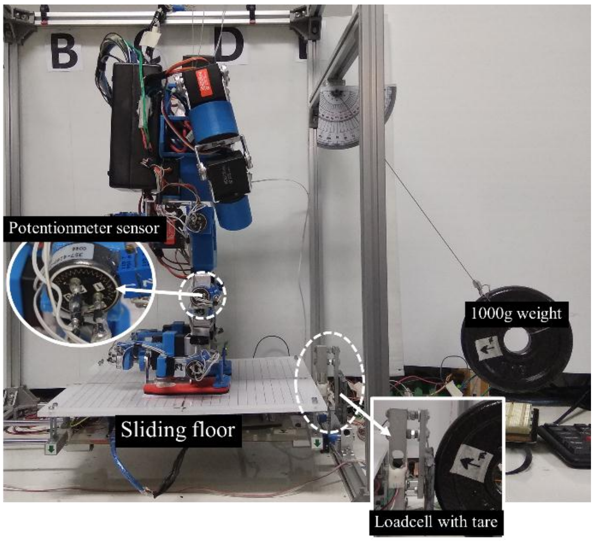

Figure 6. Experimental setup.

IV. Results

The experimental results are presented into two parts: simulation results and actual results.

A. Simulation Results

In order to determine the maximum tilt angle that cause the HR tipped over, the FK model is employed. This angle is where the CoG is pushed to the edge of the foot, shown in Fig.3-b). At this stage, the calculation from all joints gives this critical angle of $\theta_{body\,tilt}$ = 12deg and the CoG of the X-axis (X_{COG}) is 9.35cm. This makes robot become unstable. Two joint control strategies are employed to keep the CoG stay inside the foot.

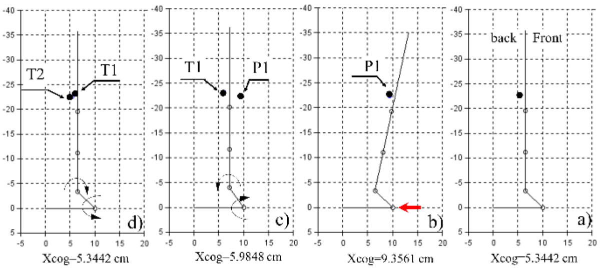

Figure 7. Ankle strategies models.

Fig. 7 shows a balance recovery simulation for the ankle strategies after the cart is hit. Four steps (a to d) of stand balancing are described as follows. Step (a), Fig. 7-

a), the HR stand balance in an initial position called the home position. Step (b), Fig. 7-b), shows movement of the HR when the cart is hit by 2.97N. This makes the CoG moves forward to the P1 position. In this position, the HR will be tipped over. Therefore, in step (c), Fig. 7-c), the CoG is controlled to move backward to the center of its sole (T1) by rotate ankle joint to -9.996deg. At this point, the heel is open and θ_{a2} is 9.994deg. The final step (d), Fig. 7-d), the CoG is moved from T1 to T2. This step the ankle is fed with 0deg which it is a home position of HR.

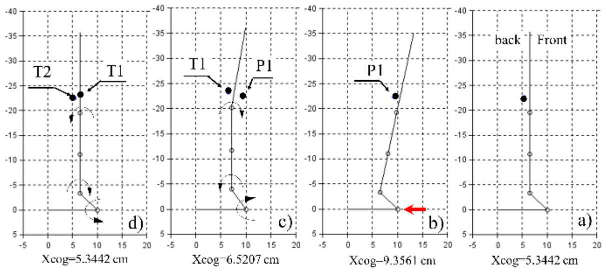

Figure 8. Ankle-Hip strategies models.

For the ankle-hip strategy, shown in Fig. 8, the processes repeat the steps of the ankle strategies but adding the hip control. The ankle is set to -10.007deg and the hip is 9.800deg. At this point, the heel is open and θ_{a2} is 10.031deg.

B. *Actual Results*

After desired angles are obtained from the simulation, these angles are applied to the real robot, illustrated in Fig 9. The tilt sensor is applied to start robot's reaction.

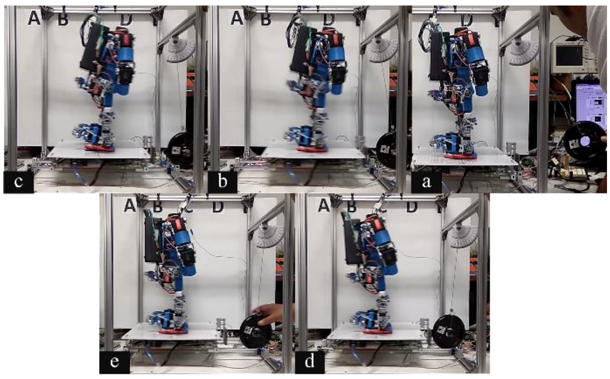

Figure 9.The eeKKU-II restore its balance using an Ankle-Hip srategy.

For the ankle strategy, the controlled ankle is moved as shown in Fig. 10 which the eeKKU-II can successfully recover from external disturbance on a slidable floor. The maximum angles are SL2= 9.57deg and SR2= -10.31deg, see Fig. 10-a). The trajectory of the X_{COG} is analyzed, as presented in Fig. 10-b). The CoG is kept behind an unstable line or the front bound at 9.35cm. Further analysis of ankle strategy is considered, as shown in Fig. 10-c). The absolute maximum jerk at the ankle joints are $2.36\text{x}10^6$deg/sec^3 and $3.31\text{x}10^5$deg/sec^3 for joints SR2 and SL2, respectively. The ankle strategy takes a recovery period of 1.0sec.

In the case of ankle-hip strategy, the controlled ankle is moved, as shown in Fig. 11, which the eeKKU-II can successfully recover with a shorter period that the previous strategy. It takes only 0.344sec to recovery from the impact. The maximum angles of the ankle and hip are SL2 = 10.994deg, SR2 = -15.203deg, SL4 = 11.123deg, and SR4 = -16.759deg, see Fig. 11-a). The trajectory of the X_{COG} is analyzed, as presented in Fig. 11-b). The CoG is kept behind an unstable line or the front bound at 9.35cm. Further analysis of ankle-hip strategy is considered, see Fig. 11-c). The absolute maximum jerk at the ankle joints and the hip joints are $6.7\text{x}10^7$deg/sec^3, $2.4\text{x}10^7$deg/sec^3, $11.8\text{x}10^7$deg/sec^3 and $11.8\text{x}10^7$deg/sec^3 for joints SR2, SL2, SR4, and SL4, respectively.

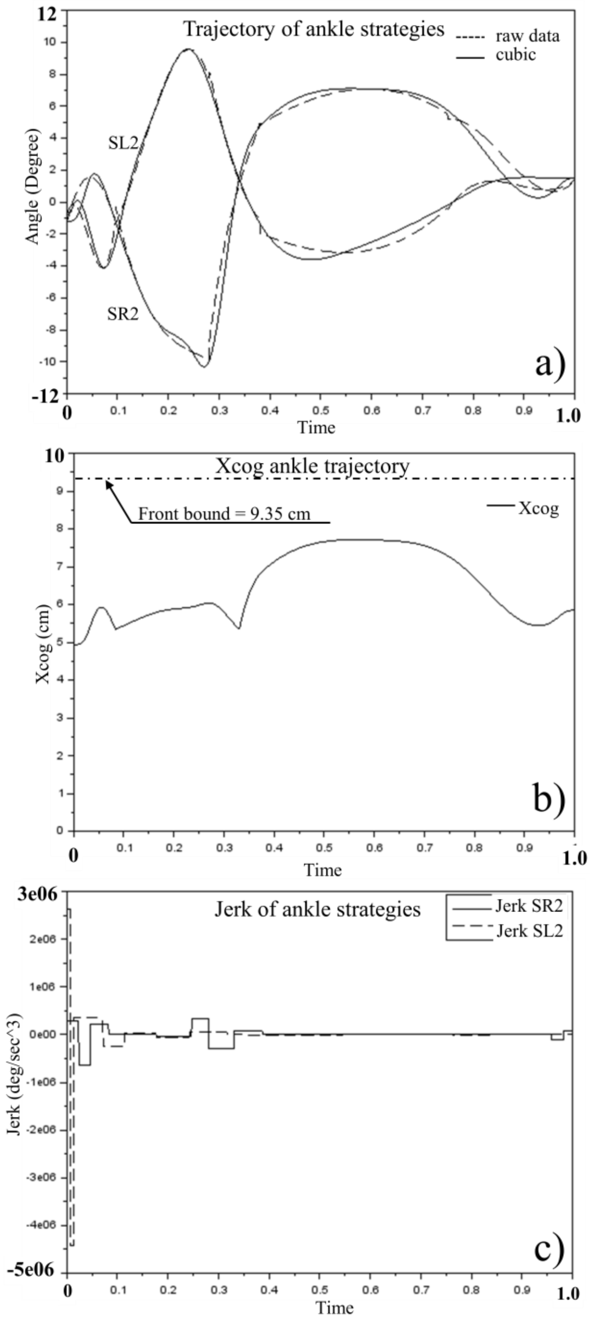

Figure 10. An ankle strategy; a) trajectory of SL2 and SR2, b) the X_{COG} path, and c) the jerk.

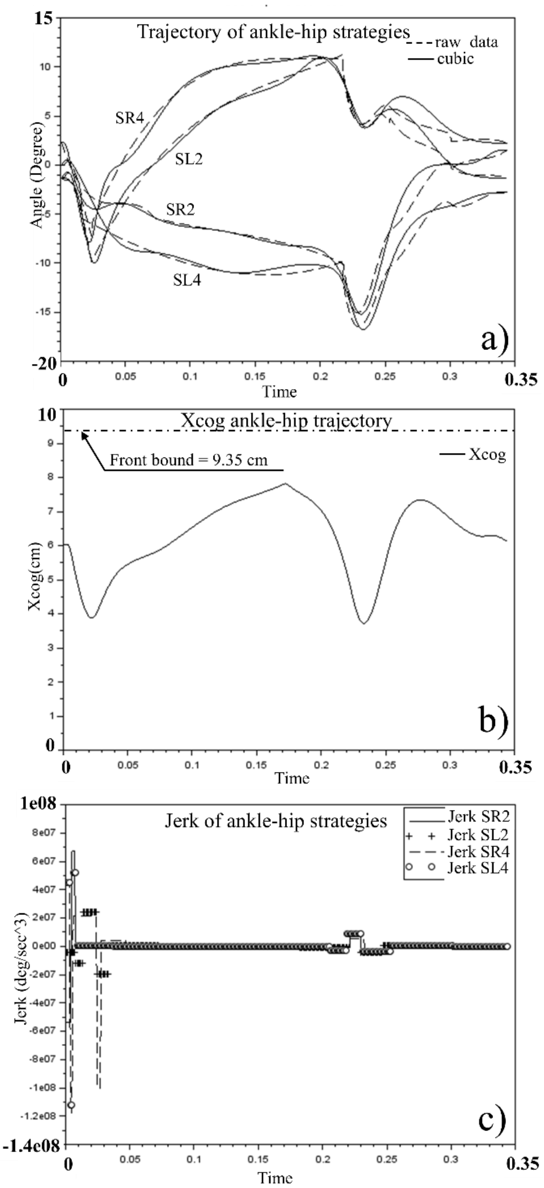

Figure 11. An ankle-hip strategy; a) trajectory of SL2, SR2, SL4, and SR4, b) the X_{COG} path, and c) the jerk.

V. Conclusion

This paper demonstrates a trajectory generation process of a humanoid robot (HR) to restore its balance from a slidable floor. Two joints control strategies are applied i.e. ankle and ankle-hip. The results show a successful balance recovery. The ankle strategy gives a balance restoration period of 1000ms while the ankle-hip strategy offers 344ms thus provides a faster recovery period of 65.6%. This can give a robot to perform other task or movement. Also, the jerk of the ankle-hip strategy is also higher. This could interpret that joint can move quicker from carrying less load and therefore prolong a mechanical wear off. The further work will focus on restore robot's balance with unknown force. The reaction period can be reduced and exploited for handle this.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Pramin Artrit is the corresponding author of this research work. He and Nattapong Nernchad conducted the experiments, obtained and analyzed data. All authors had approved the final version.

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