Balance Maintenance by Stepping for Human-like Characters against Large Perturbation

Shunsuke KUDOH[1], Taku KOMURA[2], and Katsushi IKEUCHI[1]
[1] *The University of Tokyo, Tokyo, Japan*
[2] *City University of Hong Kong, Hong Kong, China*

Abstract. We propose a method of balance maintenance for human-like characters against large perturbations. The motions that can be generated by the method enable a human-like character to maintain its balance rotating its arms, bending down and taking a step, if necessary. The former two motions are intended to control angular momentum effectively, and the method to generate these motions was proposed in our previous research. In this paper, we extend that method to allow the character to take a step if perturbation is too large for the character to otherwise keep its balance. For modeling stepping motion, we captured many human stepping motions by a motion capturing system and analyzed them.

1 Introduction

Recently, the generation of dynamically consistent motion of human-like characters has received a great deal of attention in various areas. Balance control is one of the most fundamental areas in this research. In robotics, studies on humanoid robots have long been made, and many methods of balance maintenance for humanoid robots have been proposed [5, 8, 9]. In many of these methods, generated motions are not similar to human motion because of limitations of robots, such as mass distribution, structures of joints, performance of actuators, and so on. On the other hand, in the computer graphics area, because the demand for realistic three-dimensional animation of human-like figures has been increasing, many methods to generate dynamically consistent motion which is similar to human motion have been proposed [2, 4, 6, 7]. In these research, human motion captured by a motion capturing system is often used. However, most of them use the captured motion directly after a bit of modification.

In order to realize the generation of human-like motion of balance maintenance which can be applied flexibly to various situations, it is important to observe human strategy for maintaining balance and to model the human-like motion. In our previous work, we paid attention to the fact that humans effectively control angular momentum when they maintain their balance against large perturbation, and we proposed a method of balance maintenance for a biped character [3]. Using the method, motion in which a character rotates its arms and bends down to keep its balance is generated, and large perturbation can be coped with. However, there is a limitation on the method in that both feet are fixed on the ground and cannot be moved. And that limitation, in turn, limits the magnitude of perturbation that the character can cope with. Actually, humans instinctively take a step whenever they are faced with large perturbation.

In this paper, we propose a new method to maintain balance for human-like characters. It is an extension of our previous method, and a character is allowed to take

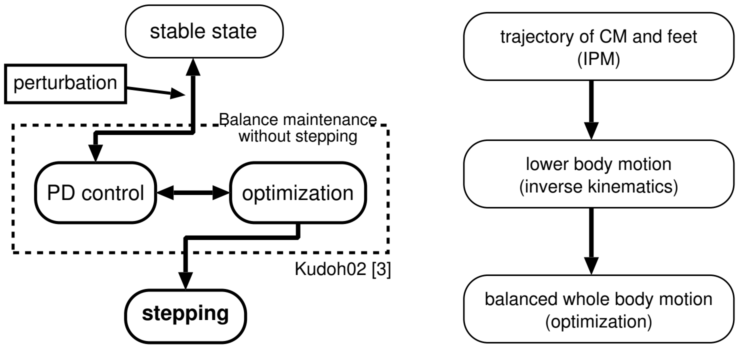


Figure 1: Overview of the system: the whole system (left) and the procedure to generate stepping motion (right)

a step to counter larger perturbation. Using the method, the motion can be generated so that the character tries to keep its balance without stepping as much as is possible, but if perturbation is too large, the character avoids falling down by taking a step. In this method, the outline of motion is first determined by an inverted pendulum model (IPM). Then, the whole body motion is generated using optimization calculation. Human motions are obtained by a motion capturing system, and then the parameters which are extracted from the obtained data are used to make the human-like characters.

2 System overview

In this paper, we propose a method for balance maintenance against large perturbation applied to a human-like biped character. The overview of the system is shown in the left of Figure 1. It roughly consists of two types of methods. One is the method in which the character maintains its balance by keeping its feet planted firmly on the ground, and the other is that in which the character take a step to prevent falling down. The former consists of two methods: PD control and optimization. PD control is a method to adjust small perturbation and the optimization is a method to cope with larger perturbation with whole body motion.

When some sort of perturbation is applied to the character, the system first tries to keep its balance by using the PD-control. When it fails, the method by optimization is adopted. If the balance is recovered, the PD-control is adopted again for final balance maintenance. When the optimization without stepping fails, the balance maintenance by stepping, which allows the character to take a step, is adopted. Motion of balance maintenance is generated frame by frame.

The methods without stepping were described in our previous paper [3]. In this paper, the method to generate stepping motion is mainly described. The overview of it is shown in the right of Figure 1. First, trajectories of the center of mass (CM) and feet are calculated by an IPM. Next, whole body motion is generated based on the trajectories by inverse kinematics (IK). Dynamic balance is not yet addressed in this step. Finally, using optimization calculation by the quadratic programming method, the motion by IK is modified to a well-balanced motion. We describe each step in the following sections.

3 Determining outline of motion by IPM

In order to generate a stepping motion, trajectories of the CM and the feet are determined by an IPM. In this paper, the stepping motion is modeled with two models. They represent phases before and after "foot contact", which is the moment when a swing leg contacts the ground. Each model is shown in Figure 2. θ and α represent the lean angle and the stepping angle. x and a represent the length between the CM and the swing foot and the length between the support foot and the swing foot. These parameters at the foot contact are written as θ_c, α_c, x_c, and a_c. In the latter model, the stepping leg is assumed to be a spring, which absorbs the shock of the foot contact. The spring constant is written as k_b.

In order to confirm the validity of the model and to determine the parameter of the model, human motion captured by a motion capturing system is used here. We used an optical motion capturing system by Vicon Motion Systems, and force plates by KISTLER Japan. The motion capturing system records the position of markers attached to a human body, and the force plates record the magnitude and the direction of force which act to the ground. Various strengths of force were applied near the CM of four subjects. The subjects were told to keep their balance, stepping only when necessary. The force was applied ten or fifteen times to each subject. They sometimes kept their balance without stepping, but at other times, they had to take a step to prevent falling down.

First, we confirm that the trajectory of the CM can be approximated by the IPM. Figure 3 shows the topical trajectories of the lean angle, θ for each subject. The red points represent the captured data and the green points represent simulation results. In the simulation, an IPM is constructed so that it has the same mass and inertia to the subject of upright posture, and the trajectory of it under the same initial position and velocity to the subject is calculated by forward dynamics. The graphs show that the trajectory of the CM during a single support phase can be approximated by the IPM. In more detail, the gap of the captured data and the simulation results are shown as the table in Figure 3. It shows the average and the standard deviation of the ratio of the difference of the lean angle between the captured data and the simulation result at the foot contact to the lean angle. Although individual variation is observed, the gap is generally within 10%.

Next, α_c is determined. Ratio of α_c and θ_c is well-converged independent of the subjects as shown in Table 1. It shows the average and the standard deviation of α_c/θ_c about each subject. According to it, it can be said that α_c/θ_c is always about 1.20.

Finally, spring constant k_b is determined. Before calculating k_b, the validity of the model has to be confirmed. If the model is valid, the following equation is satisfied:

$$f_g = k_b(x - x_c), \tag{1}$$

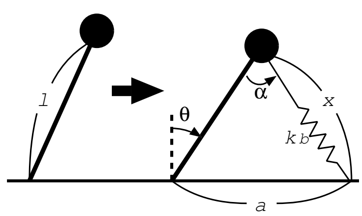
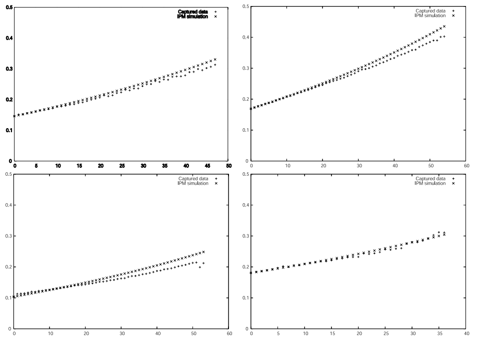


Figure 2: IPM (before and after "foot contact")



subject	AVG	STD
1	11.0	5.9
2	5.0	3.6
3	11.7	7.2
4	4.1	4.6
total	8.5	6.6

Figure 3: Gaps between the lean angle (θ) of the subjects and the sumulation result: In the left four graphs, the points of '+' are the captured data and the points of '×'are the simulation result. The vertical axis represents the lean angle [radian], and the horizontal axis represents the frame index number. The right table shows average (AVG) and standard deviation (STD) of gaps between the captured data and the simulation result (%).

subject	AVG	STD
1	1.29	0.215
2	1.07	0.221
3	1.30	0.167
4	1.16	0.300
total	1.20	0.256

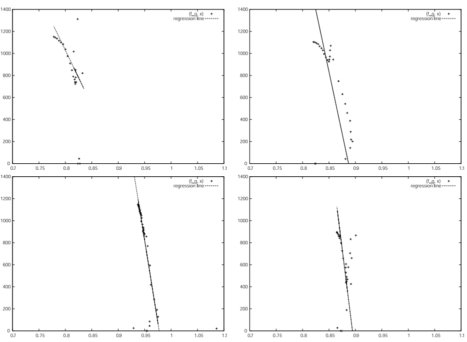
Table 1: Average (AVG) and standard deviation (STD) of α_c/θ_c

where f_g is the ground reaction force acting to the contact foot. The value of f_g is measured by the force plates and the value of x is measured by the motion capturing system. If the above equation is satisfied, points of (f_g, x) lie on a strait line. Figure 3 shows graphs that the actual data from motion capturing system is plotted. The points surely lie on a strait line, which is drawn as green line. The spring constant, k_b, is obtained as the gradient of the regression line in the above graphs. The spring constant calculated from the captured data is shown as the table in Figure 3. Values of k_b converge about one subject, but the value is deferent among the subjects.

4 Determining lower body motion using IK

In this section, the way to generate lower body motion using an IK is described. The motion is generated from the designed trajectories obtained in the previous section. IK calculation is performed twice. IK for the CM is solved first, and then, IK for the foot is solved. In the former, the link structure from the ankle of the support leg to the CM is considered and in the latter, the link structure from the hip joint of the swing leg to the heel is considered (Figure 5). The destination of the CM in solving IK is determined from the trajectory of the CM which was calculated by the IPM. The destination of the stepping foot is determined from a B-spline curve connecting from the point where the swing foot leaves the ground to the point of the foot contact. With regard to upper body motion, we consider it in the next section, and now the upper body posture in the previous frame is used as the upper body posture.

The way to solve IK is as follows. Now, let $\boldsymbol{\theta} = (\theta_0, \ldots, \theta_n)^T$ be angles of the joints



subject	AVG	STD
1	25.1	5.43
2	17.9	7.03
3	12.7	4.24
4	13.5	4.33
total	18.5	7.54

Figure 4: Spring constant k_b: The left four graphs show the distribution of (f_g, x) and its regression line. The vertical axis represents f_g[N] and the horizontal axis represents x[m]. The graphs are typical cases for every subjects. k_b is a gradient of the regression line. The right table shows the average (AVG) and the standard deviation (STD) of k_b k[N/m].

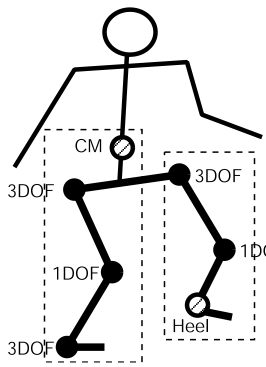


Figure 5: The link structures for solving IK

related to the link structure for considering IK structure, $\boldsymbol{p}_i$ and $\boldsymbol{z}_i$ be the position and the rotational axis of each DOF, and $\boldsymbol{r} = (\boldsymbol{P}^T, \boldsymbol{\Omega}^T)^T$ be the position and the rotation of the end effectors, such as the CM and the stepping foot. The angles of three degrees-of-freedom (DOF) joints and the rotation are expressed by Euler angles. The relationship between $\boldsymbol{r}$ and $\boldsymbol{\theta}$ is written by Jacobian:

$$J = \begin{pmatrix} \boldsymbol{z}_0 \times (\boldsymbol{P} - \boldsymbol{p}_0) & \cdots & \boldsymbol{z}_i \times (\boldsymbol{P} - \boldsymbol{p}_i) & \cdots \\ \boldsymbol{z}_0 & \cdots & \boldsymbol{z}_i & \cdots \end{pmatrix}. \quad (2)$$

The IK problem is solved using the pseudo-inverse matrix, $J^T(JJ^T)^{-1}$, iteratively. The actual procedure of solving the IK is as shown in Figure 6.

5 Determining whole body motion by optimization

In the previous section, we did not yet consider the dynamic balance of the character. In this section, we describe a method for generating well-balanced motion. In the previous section, because motion of only the lower body was considered, there was redundancy in the upper body. Therefore, the balance could be maintained by making use of the redundancy.

Let $\boldsymbol{\theta}$ be the angles of the all joints. The problem in this section can be written as "obtaining angular acceleration $\ddot{\boldsymbol{\theta}}$ which makes the Zero Moment Point (ZMP) within

```
set r for initial θ
while (‖r_dest − r‖ > δ) {
    obtain J for θ
    Δθ = J^T (J J^T)^{-1} (r_dest − r)
    renew θ as θ + Δθ
    renew r for new θ
}
```

Figure 6: The procedure for solving IK

the foot support area". A ZMP is a concept proposed by Vukobratovic et al. [1] and it is the point where the moment induced by the ground reaction becomes 0. It is always within the support area if motion is dynamically consistent. The unknown variable in this problem is angular acceleration $\ddot{\boldsymbol{\theta}}$ because only it can be directly controlled by the system. Angles $\boldsymbol{\theta}$ and angular velocity $\dot{\boldsymbol{\theta}}$ are not directly controllable.

In this method, the quadratic programming method is used to obtain the optimal angular acceleration. Because it allows only linear formulae as constraints, it has to be expressed as linear formulae whether the ZMP is within the support area or not. From the definition of a ZMP, a ZMP can be regarded as the point where the all ground reaction force is acting. Therefor, the ZMP is written as

$$\boldsymbol{n} = (\boldsymbol{p} - \boldsymbol{s}) \times \boldsymbol{N}, \tag{3}$$

where $\boldsymbol{p}$ is the ZMP, $\boldsymbol{n}$ is the moment around the CM, $\boldsymbol{s}$ is the position of the CM, and $\boldsymbol{N}$ is the sum of the ground reaction force. Now let $\boldsymbol{p}$ be $(p_x, 0, p_z)^T$. From the equation of motion, $\boldsymbol{N} = m(\ddot{\boldsymbol{s}} - \boldsymbol{g})$, and thus, the equation (3) can be solved as

$$p_x = \frac{n_z + s_x m(\ddot{s}_y - g_y) - s_y m \ddot{s}_x}{m(\ddot{s}_y - g_y)} \tag{4}$$

$$p_z = -\frac{n_z - s_z m(\ddot{s}_y - g_y) + s_y m \ddot{s}_z}{m(\ddot{s}_y - g_y)}. \tag{5}$$

The position of the CM is a function of $\boldsymbol{\theta}$. When we write it as $s(\boldsymbol{\theta})$, the acceleration of the CM, which is the second derivative of the position, can be expressed as a linear formula about the angular acceleration:

$$\ddot{s} = \sum_i \frac{\partial s}{\partial \theta_i} \ddot{\theta}_i + \sum_{i,j} \frac{\partial^2 s}{\partial \theta_i \partial \theta_j} \dot{\theta}_i \dot{\theta}_j. \tag{6}$$

Note that only $\ddot{\theta}$ is a variable here and θ and $\dot{\theta}$ are regarded as constants. The angular momentum of the whole body is a function of $\boldsymbol{\theta}$ and $\ddot{\boldsymbol{\theta}}$. When we write it as $l(\boldsymbol{\theta}, \ddot{\boldsymbol{\theta}})$, the moment around the CM, which is the derivative of the angular momentum, can be expressed as a linear formula about the angular acceleration:

$$\dot{l} = \sum_i \frac{\partial l}{\partial \theta_i} \ddot{\theta}_i + \sum_i \frac{\partial l}{\partial \dot{\theta}_i} \dot{\theta}_i. \tag{7}$$

From above discussion, it is proved that the acceleration of the CM and the moment acting around the CM can be expressed as

$$\sum_i c_i \ddot{\theta}_i + d. \tag{8}$$

The coefficients of the equation are determined by solving forward dynamics about $\ddot{\boldsymbol{\theta}}^i$ for all i:

$$\ddot{\boldsymbol{\theta}}^i = (0, \ldots, 0, \overset{\overset{i\text{-th}}{\vee}}{1}, 0, \ldots). \tag{9}$$

Therefore, the numerators and the denominators in the equation (4) and (5) can be written as linear formulae about $\ddot{\boldsymbol{\theta}}$, and then, the ZMP can be written as follows:

$$p_x = \frac{\boldsymbol{c}_x^T \ddot{\boldsymbol{\theta}} + d_x}{\boldsymbol{c}_c^T \ddot{\boldsymbol{\theta}} + d_c}, \quad p_z = \frac{\boldsymbol{c}_z^T \ddot{\boldsymbol{\theta}} + d_z}{\boldsymbol{c}_c^T \ddot{\boldsymbol{\theta}} + d_c}, \tag{10}$$

where $\boldsymbol{c}_*$ and d_* are constants.

Because the motion of the lower body is determined as that obtained in the previous section, the balance maintenance is performed by changing the angular acceleration of the joints of the upper body. Let $\boldsymbol{\theta}_{\text{dof}}$ be the angles of the joints related to the procedure, and the following quadratic programming problem is taken to obtain the optimal acceleration.

$$\text{min.} \quad \ddot{\boldsymbol{\theta}}_{\text{dof}}^T A \ddot{\boldsymbol{\theta}}_{\text{dof}} \tag{11}$$

$$\text{s.t.} \quad x_{\min} \leq p_x \leq x_{\max} \tag{12}$$

$$z_{\min} \leq p_z \leq z_{\max} \tag{13}$$

$$\ddot{\boldsymbol{\theta}}_{\max} \leq \ddot{\boldsymbol{\theta}} \leq \ddot{\boldsymbol{\theta}}_{\max} \tag{14}$$

The objective function aims to minimize the square sum of the angular acceleration. It is in order to generate low-cost motion. A is a weight matrix. $x_{\text{min,max}}, z_{\text{min,max}}$ determine the support area in which the ZMP exists. The constraints about the ZMP can be written as linear inequations using equations (10). For example, $x_{\min} \leq p_x$ is written as follows:

$$(\boldsymbol{c}_x - x_{\min}\boldsymbol{c}_c)^T \ddot{\boldsymbol{\theta}}_{\text{dof}} + (d_x - x_{\min} d_c) \geq 0. \tag{15}$$

6 Experiment

Figures 7–9 show the results of computer simulation based on the methods described in the previous sections. They show the motion every 0.08 second. The time step in the calculation is 0.01 second. The control begins 0.2 second after perturbation is applied in order to simulate the delay of response in humans' case. Yellow bars in the figures stand for the IPM used for generating steps.

Figure 7 is the result when the force of 300N is applied to near the CM of the character during 0.4 second. At first, the balance maintenance by keeping the feet on the ground is taken and the character rotates its arms to keep its balance. At last, however, it becomes impossible for the character to keep its balance using the method, and then, the balance maintenance by stepping is applied.

Figure 8 is the result when the force of 300N is applied during 0.1 second. In this case, stepping is not necessary, and the character keeps its balance using only the balance maintenance by keeping the feet on the ground. Figure 9 is the result when the same force is applied during the same time, but in this case, the balance maintenance by keeping the feet on the ground is not used, and the balance maintenance by stepping is taken directory after PD-control. Comparing with Figure 7, the stepping distance is smaller. Thus, various motions for balance maintenance can be generated according to situations by changing the timing when stepping is started.

7 Conclusion

In this paper, we have proposed a method of balance maintenance when large perturbation is applied to human-like characters. The proposed method is an extension of our previous method, which generates motion to maintain balance controlling angular momentum by moving the whole body, and it allows the character to take a step to avoid falling down. To generate a stepping motion, first, rough trajectories of the CM and the feet are calculated using IPM; next, the upper body motion is generated based on the trajectories using IK; finally, a well-balanced whole body motion is generated by the optimization. In order to confirm the validity of the model and to determine the parameters of the model, human motion captured by a motion capturing system is used.

Acknowledgment

The authors would like to thank Prof. Minoru Ueda for his support when we used the motion capturing system in Aizu University. This research is supported in part by Japan Science and Technology Corporation under the Ikeuchi CREST project.

References

[1] M. Vukobratovic, B. Borovac, D. Surla, and D. Stokic, *Scientific Fundamentals of Robotics 7. Biped Locomotion: Dynamics Stability, Control and Application*, SpringerVerlag, New York, 1990.

[2] Seyoon Tak, Oh-young Song, and Hyeong-Seok Ko, *Motion Balance Filtering*, Computer Graphics Forum, 19(3):435–446, 2000.

[3] Shunsuke Kudoh, Taku Komura, and Katsushi Ikeuchi, *The Dynamic Postural Adjustment with the Quadratic Programming Method*, Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems, pp.2563–2568, 2002

[4] C. K. Liu and Zordan Popvić, *Synthesis of Complex Dynamic Character Motion from Simple Animations*, ACM Transactions on Graphics (SIGGRAPH02), 21(3):408–416, 2002

[5] Koichi Nishiwaki, Satoshi Kagami, Yasuo Kuniyoshi, Masayuki Inaba, and Hirochika Inoue, *Online Generation of Humanoid Walking Motion based on a Fast Generation Method of Motion Pattern that Follows Desired ZMP*, Proceedings of the IEEE International Conference on Robotics and Automation, pp.2684–2689, 2002

[6] Victor B. Zordan and Jessica K. Hodgins, *Motion capture-driven simulations that hit and react*, ACM SIGGRAPH Symposium on Computer Animation, 2002.

[7] Anthony C. Fang and Nancy S. Pollard, *Efficient Synthesis of Valid Human Motion*, ACM Transactions on Graphics (SIGGRAPH03), 22(3):417–426, 2003

[8] Ryo Kurazume, Tsutomu Hasegawa, and Kan Yoneda, *The Sway Compensation Trajectory for a Biped Robot*, Proceedings of the IEEE International Conference on Robotics and Automation, pp.925–931, 2003

[9] Shunji Kajita, Fumio Kanehiro, Kenji Kaneko, Kiyoshi Fujiwara, Kensuke Harada, Kazuhito Yokoi, and Hirohisa Hirukawa, *Resolved Momentum Control: Humanoid Motion Planning based on the Linear and Angular Momentum*, Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems, pp.1644–1650, 2003

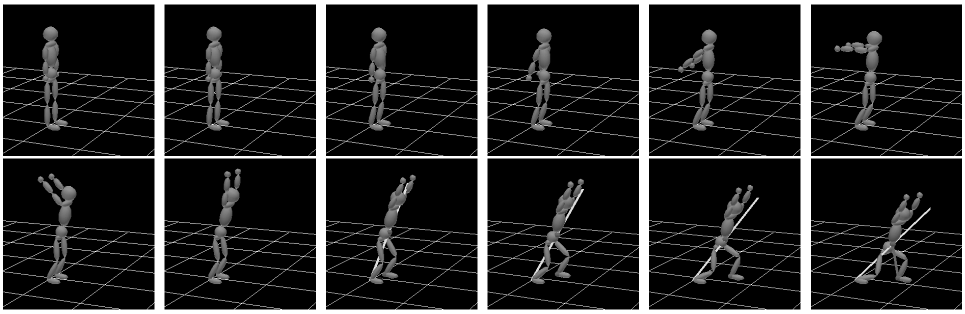


Figure 7: Balance maintenance by stepping (300N, 0.4sec)

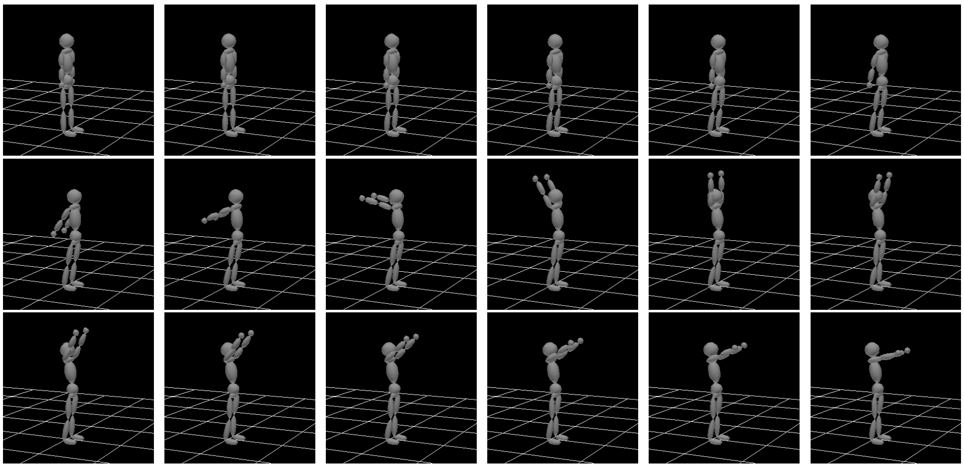


Figure 8: Balance maintenance without stepping (300N, 0.1sec)

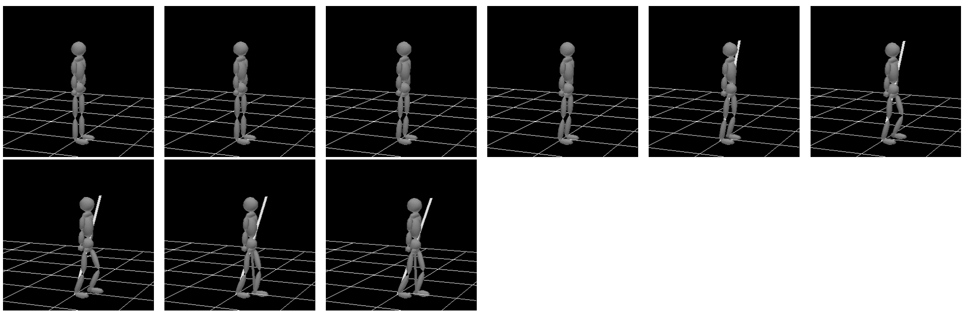


Figure 9: Balance maintenance by stepping (300N, 0.1sec)