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Shuffle turning in humanoid robots through load distribution control of the soles

Masanao Koeda*†, Toshitatsu Ito‡ and Tsuneo Yoshikawa‡

†*Department of Computer Science, Faculty of Information Science and Arts, Osaka Electro-Communication University, Kiyotaki 1130-70, Shijonawate, Osaka 575-0063, Japan*
‡*Department of Human and Computer Intelligence, College of Information Science and Engineering, Ritsumeikan University, Noji-Higashi 1-1-1, Kusatsu, Shiga 525-8577, Japan*

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SUMMARY
This paper proposes a novel shuffle turning method for a humanoid robot that controls the load distribution of the soles of the robot's feet. Turning motions of a humanoid robot are conventionally performed through a repeated foot stepping motion. However, this motion is inefficient and time-consuming. In our method, the feet are slid along the floor without a stepping movement. In order to reduce the friction with the floor and to achieve the correct shuffle turning motion, a non-uniform load distribution of the soles is controlled. Experiments using a humanoid robot were conducted on two floors with differing friction amounts, and the validity of the proposed method was verified.

KEYWORDS: Humanoid robot; Shuffle turn; Slip; Load distribution; Sole.

1. Introduction

Humans routinely move within narrow spaces and under constrained postures during their everyday activities. While working in a kitchen, for example, cooking, washing dishes, grabbing a piece of cookware, or doing some other task related to their work, cooks are required to move around a sink area in a stooped or knee-bent position. In automobile assembly lines, workers need to move within narrow spaces and in constrained postures while assembling car parts. In nursing care, support personnel may have to lift a patient from his or her bed with their arms in a constrained position while turning to place the patient in a wheelchair within a narrow medical ward. Finally, in plant construction tasks, field workers need to perform much of their work in narrow spaces and constrained postures.

Many researchers[1–4] have studied the stable walking ability of humanoid robots. Biped robots conventionally perform walking and turning motions through repeated foot stepping as they move around their environment. These kinds of motions are easy to generate because these can be treated similarly as walking motions. However, foot stepping is inefficient, time-consuming, unstable, and generally unsuitable for use in narrow spaces under constrained postures, as shown in Fig. 1.

* Corresponding author. E-mail: koeda@isc.osakac.ac.jp

Few studies have targeted the turning motions of humanoid robots. As illustrated in Fig. 2, the conventional motion loops of humanoid robots are generated using two states only: standing and stepping. Motions generated by combining these two states are suitable for mid- and long-range movements. However, they are not suitable in narrow spaces under constrained positions. Shuffling is a newly developed state but has received little attention from researchers.

Recent research has focused on the stepless motion of humanoid robots. Nishikawa[5] developed a humanoid robot that has an extrusion pin on each foot, and can thus realize a stepless turning movement. However, the proposed robot needs a specialized mechanism on its feet, and the effects of floor friction have not been considered. We previously proposed a novel stepless turning method for humanoid robots, called "shuffle turn,"[6] which uses a common foot mechanism. This research is based on the idea that wide and continuous changes in the support polygon contribute to high stability during stepless motions. In order to verify the validity of our proposed method, we conducted experiments on 90° shuffle turning motion using a point of contact between one corner of the pivoting foot and the floor. Miura *et al.*[7] showed a model in which a minimal amount of energy is consumed from floor friction while both feet are in a slip turning motion. They conducted their experiments using a humanoid robot and concluded that the friction coefficient of the floor had no effect on slip turning. Afterwards, the model was extended to study asymmetric load balance, and a friction coefficient was input into the model equation.[8] Hashimoto *et al.*[9] investigated a quick slip turn for a humanoid robot using a passive toe joint and showed the high-energy efficiency of a slip turn. There have been many researches on the walking movements of biped robots on low-friction floors.[10–13] These studies have focused on slip prediction, falling avoidance, or slip recovery.

For precise and smooth stepless turning, the effects of floor friction should be taken into account, and the friction force should be controlled. As a next step in our research, we have taken notice of the human turning motion, as illustrated in Fig. 3. The red parts in the figure indicate high-load regions, which are the rotation centers of each foot while turning.

In this paper, we propose a new shuffle turning motion in which both feet slip simultaneously while their load distributions are controlled. There are various patterns of

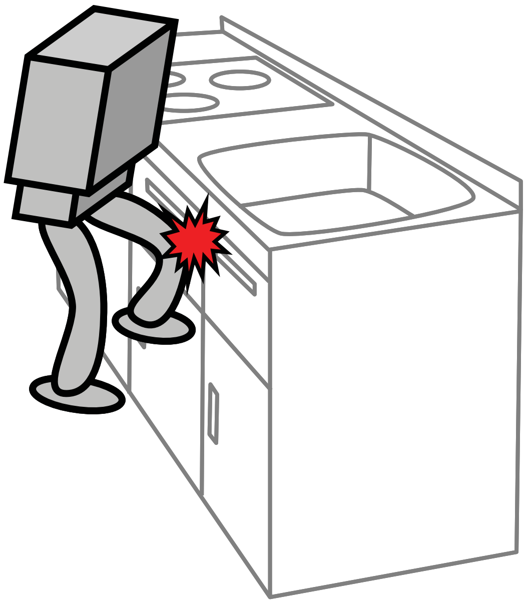

Fig. 1. Motivation.

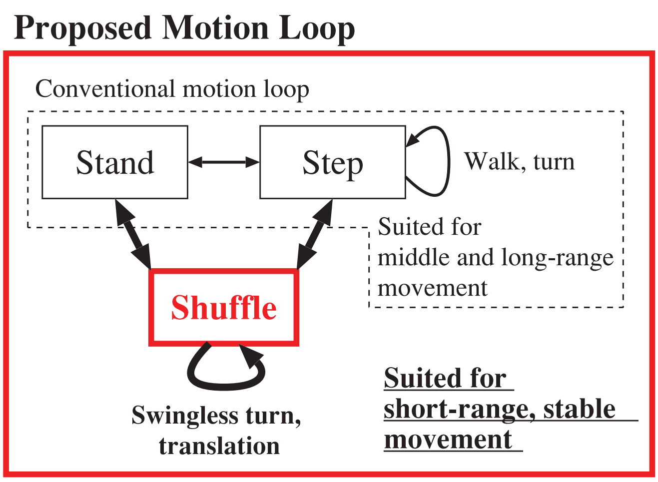

Fig. 2. Conceptual diagram.

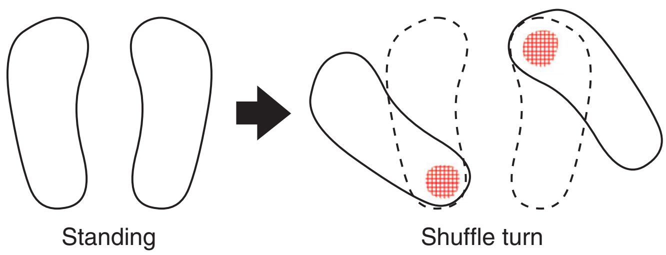

Fig. 3. Conceptual image of shuffle turning in a human.

load distribution on the soles. By selecting the proper load distribution pattern, the effects of friction are reduced and correct turning can be achieved. In order to verify the proposed method, we conducted experiments using a humanoid robot under different amounts of floor friction. We confirmed the validity of the method by comparing the turning angles and deviation of the rotational center.

2. Shuffle Turning by Controlling Load Distribution

In terms of foot motion, shuffle turning can be classified into the two typical motions, as illustrated in Fig. 4. One is sequential motion and the other is simultaneous motion. As mentioned above, we previously studied sequential shuffle turning. Therefore, in this paper, we target the simultaneous motion, as shown in Fig. 4(b).

It is thought that shuffle turning is affected more by floor friction than by the conventional turning motion. In particular, balancing the mass load of the robot on both soles, and maintaining the soles in a horizontal position, has a strong effect and may result in a variable and unstable rotation.

There are a number of varying combinations for how loads can be distributed across the soles. Most humanoid robots have flat and square soles; patterns of their typical load distribution are shown in Fig. 5. These patterns should be selected as required by the situation. In this paper, we focus on a non-uniform and symmetrical distribution and a uniform distribution, as shown in patterns (a) and (e), respectively, of Fig. 5.

3. System Configuration

Our experimental system consists of a humanoid robot HOAP-2 and a host PC. HOAP-2 is a commercial humanoid robot developed by Miyachi Systems Corporation (http://www.miyachi-sys.com/). The robot has 25 degrees of freedom (DOF). The height of the robot is 500 mm and its weight is approximately 7 kg. The size of its foot is 98 mm × 63 mm. Four force sensors were mounted onto each foot, and three-axis acceleration/angular sensors are equipped in its body. The soles of the feet are made of polyoxymethylene (POM). Figure 6 illustrates the size of the feet, CH. 0, 1, 2, and 3 show the positions of the force sensors. The robot is controlled in 1 ms through a PC running RT-Linux OS. The distance between the right and left foot is 47 mm at the initial standing position.

4. Motion Generation of a Shuffle Turn

The coordination system used for the robot's feet is illustrated in Fig. 7. The origin position of the coordination system, $\sum_B$, is arranged in the mid-point between the rotational center points. The positions of the rotational center of the right and left soles at the initial state are described as

$$\mathbf{r}_\mathrm{s} = (r_{sx}\ r_{sy})^\mathrm{T}, \tag{1}$$

$$\mathbf{l}_\mathrm{s} = (l_{sx}\ l_{sy})^\mathrm{T}. \tag{2}$$

After a shuffle turn of θ is conducted, the positions of the rotational centers in $\sum_B$ can be written as

$$\mathbf{r}_\mathrm{e} = \mathbf{R}\mathbf{r}_\mathrm{s}, \tag{3}$$

$$\mathbf{l}_\mathrm{e} = \mathbf{R}\mathbf{l}_\mathrm{s}, \tag{4}$$

$$\mathbf{R} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}, \tag{5}$$

The joint angles of the leg are calculated from $\mathbf{r}_e$ and $\mathbf{l}_e$ by solving the inverse kinematics problem.

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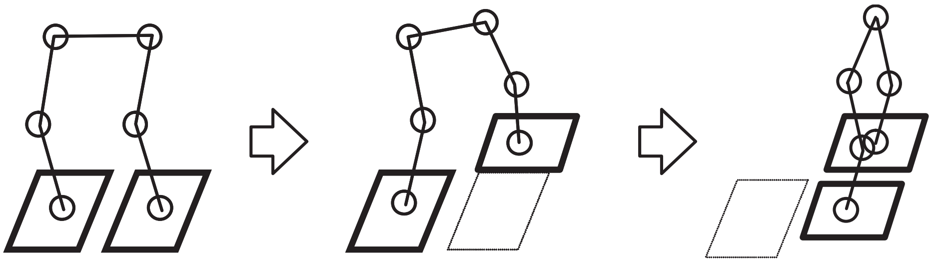
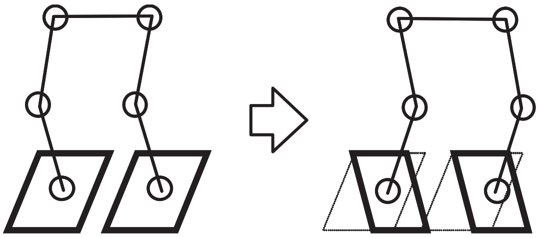


(a) Sequential shuffling.



(b) Simultaneous shuffling.

Fig. 4. Typical feet motion during shuffle turning.

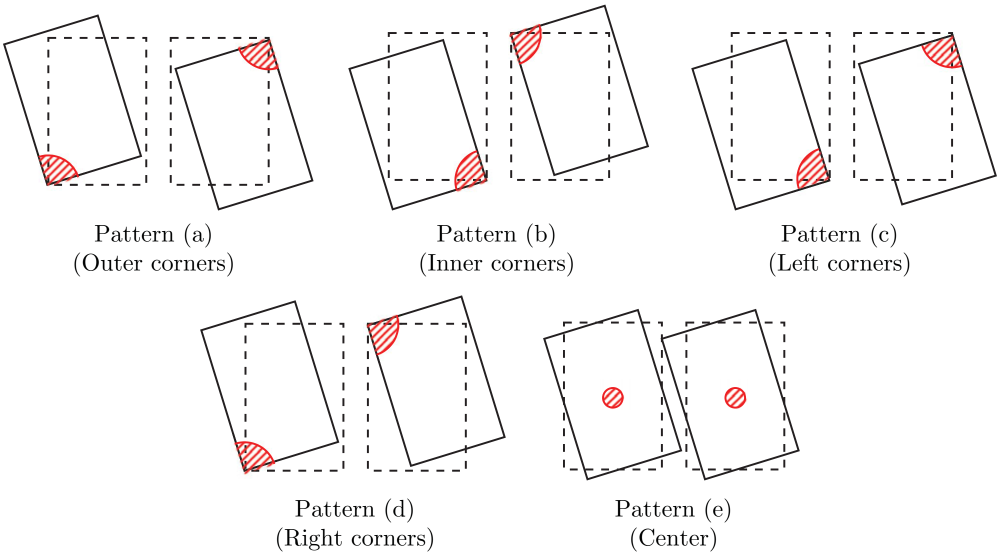
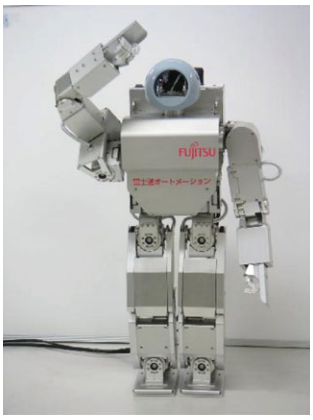


Fig. 5. Variety of load distribution. Patterns (a)–(d) are non-uniform load distributions, while (e) is uniform load distribution.



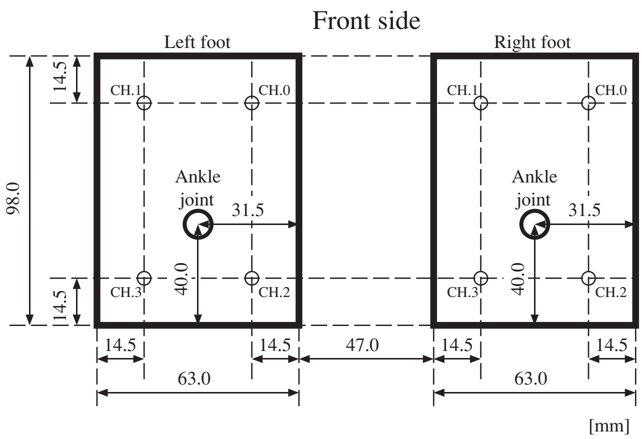


Fig. 6. Humanoid robot HOAP-2 and its feet specifications.

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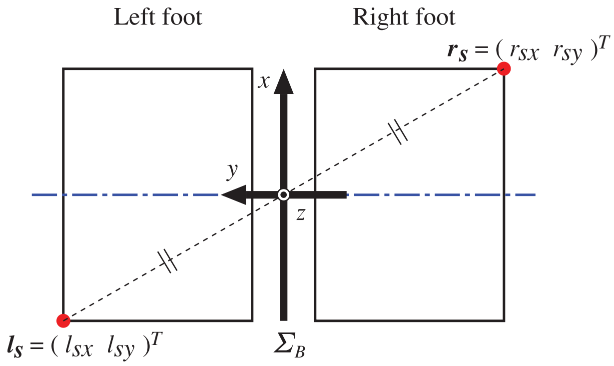
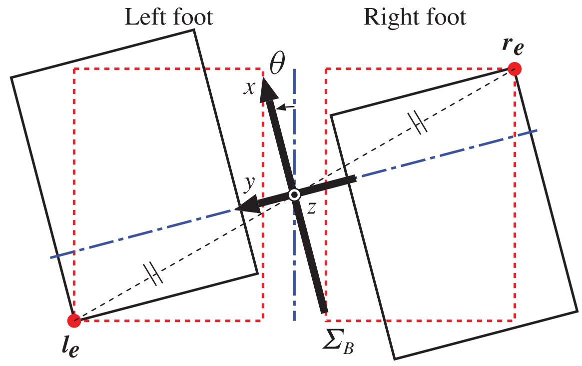


(a) Starting feet position.



(b) Ending feet position.

Fig. 7. Coordination system and rotational centers.

In order to change the load distribution in pattern (a) (Fig. 5), the joints of the ankle are rotated by $+1^\circ$ about the x, y axis in the right foot, and by -1° about the x, y axis in the left foot, before turning. In pattern (e), the ankle joints are maintained in a constant horizontal position.

5. Friction Coefficient of the Floor

In the following experiments, two types of floors with different friction coefficients were used. The friction coefficients were measured using the measurement device, as shown in Fig. 8. The device had a vice bench with a tiltable clamp, and the tilt angle could be measured easily using a scale. A piece of plastic of the same material and size of the sole was clamped to the floorboard using the vice.

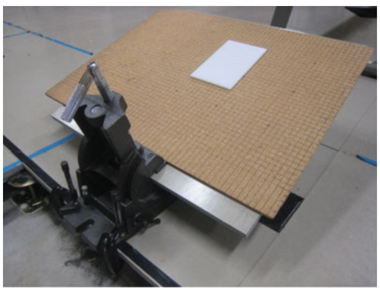
When tilting the vice, the piece of plastic started slipping on the board. The static friction coefficient, μ, was calculated using the following equation:

$$\mu = \tan \rho, \tag{6}$$

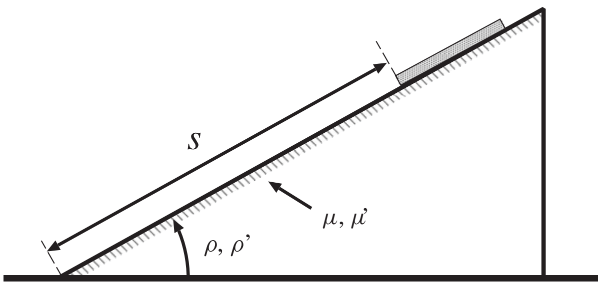
where ρ is the tilting angle of the clamp.

In addition, on the assumption that the piece of plastic has a constant acceleration, the dynamic friction coefficient μ' can be calculated using

$$\mu' = \tan \rho' - \frac{2s}{t^2 g \cos \rho'}, \tag{7}$$



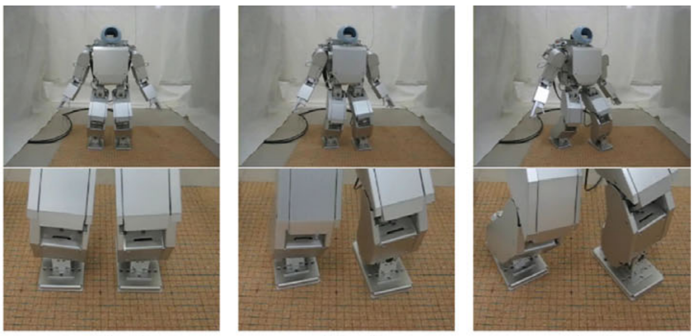
(a) Measurement device



(b) Parameters

Fig. 8. Device for measuring floor friction.

(a) Low-friction floor.



(b) High-friction floor.

Fig. 9. Experimental results of pattern (a).

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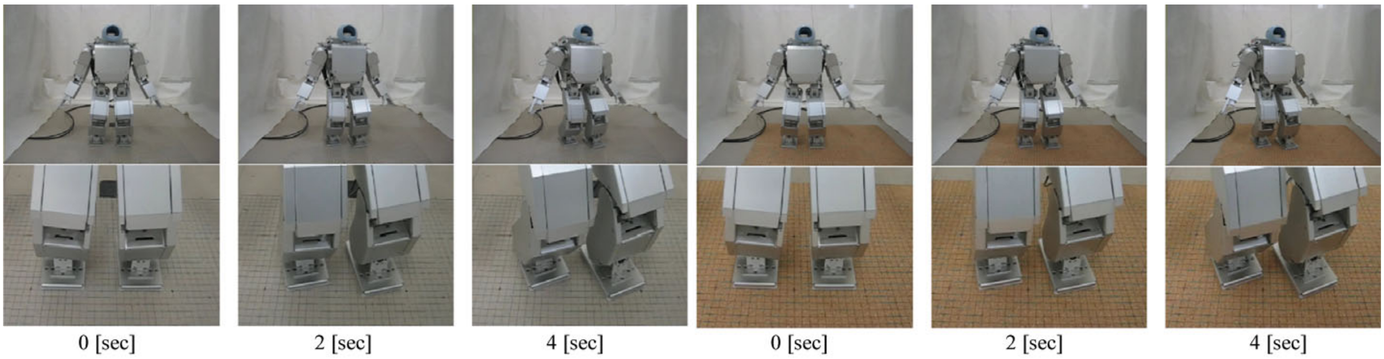


(a) Low-friction floor. (b) High-friction floor.

Fig. 10. Experimental results of pattern (e).

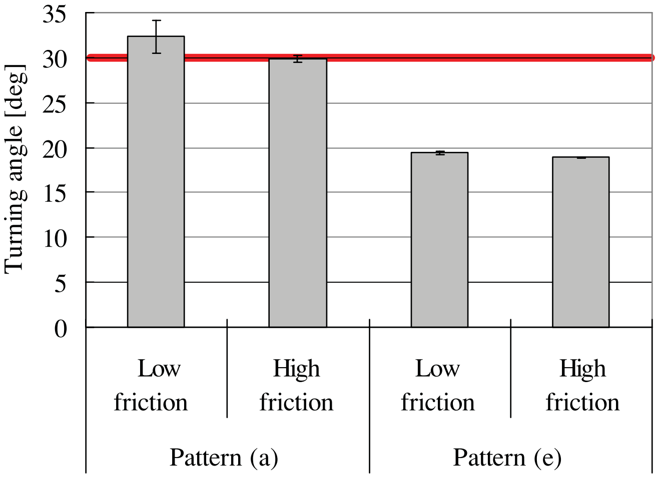


Fig. 11. Turning angle.

where ρ' is the tilting angle of the clamp, s is the slipping length, t is the slipping time, and g is the acceleration of gravity.

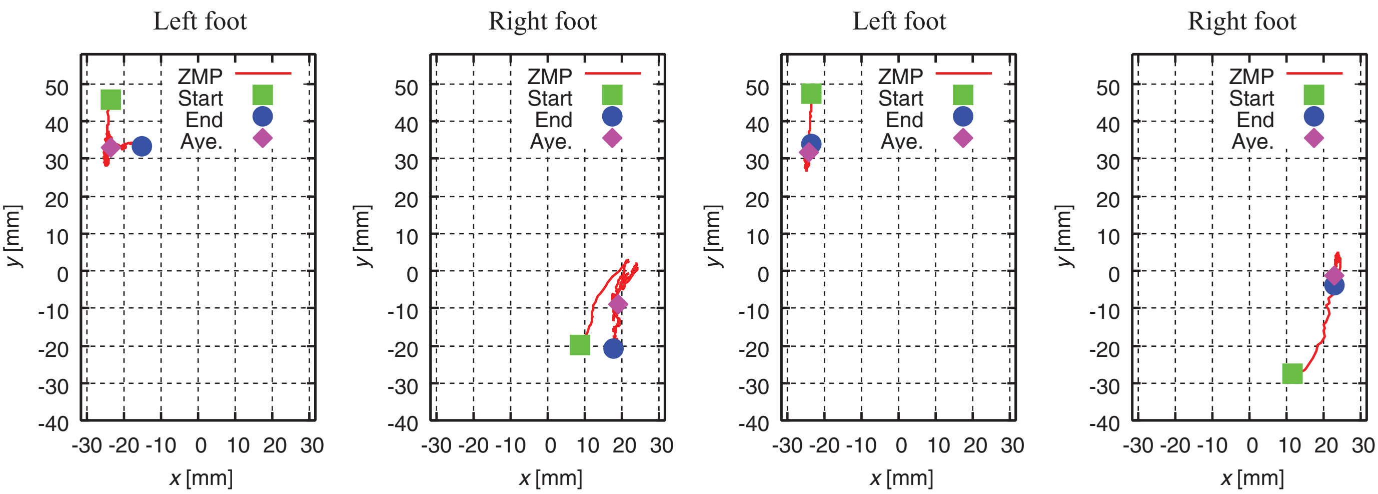
Using these equations, the friction coefficients of the two types of floor material were measured, the results of which are shown in Table I.

Table I. Properties of floor materials.

Material	Static friction coefficient, μ	Dynamic friction coefficient, μ'
Linoleum	0.24	0.24
Cork	0.47	0.43

6. Experiments and Results

In all of the following experiments, a rotation angle, $\theta = 30°$, for 4 s and a constant angular velocity of 7.5°/sec were used. Our selection of this rotation angle was because of the limited joint motion of our humanoid robot. If a humanoid robot has a wider range of joint motion, it can generate a larger rotation angle. In order to compare the experimental results under same conditions, the robot was controlled using an open-loop control scheme without the use of sensor feedback. Each experiment was conducted five times. The rotation angle was measured using an angular sensor mounted on the robot, and the deviation of the rotational center was measured using a ruler. Figures 9 and 10 show snapshots of the experiments. The grid lines on the floor were drawn at 10-mm intervals, and the motions of the feet were measured using the grid.



(a) Low-friction floor. (b) High-friction floor.

Fig. 12. ZMP trajectory of pattern (a).

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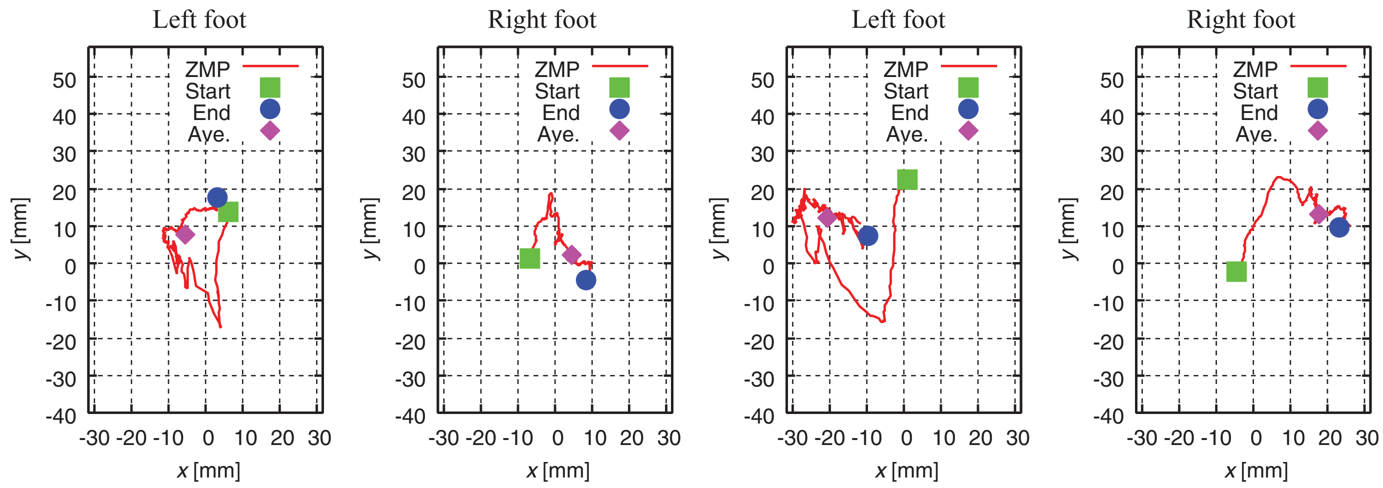

(a) Low-friction floor. (b) High-friction floor.

Fig. 13. ZMP trajectory of pattern (e).

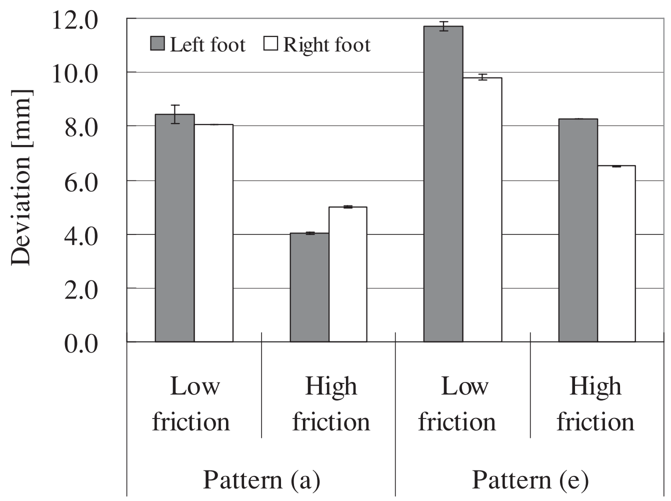

Fig. 14. Deviation of rotational center.

The average rotation angle after turning is shown in Fig. 11. When using the feet motion of pattern (e) of Fig. 5, the turning angle was approximately 20°, and did not reach the target angle 30°, which is shown with red bar. On the other hand, using pattern (a), the angle was close to the target angle, and its shuffle turning motion was completed correctly. These results suggest that shuffle turning using load distribution works effectively and the appropriate load distribution is necessary for correct shuffle turning.

Figures 12 and 13 show the Zero Moment Point (ZMP) trajectory during this experiment. Red, green, blue, and purple dots indicate the timeline, and the starting, ending, and average positions of the ZMP, respectively. A slight unintended displacement occurred because of the feedforward control. However, the ZMP was near the corners of the feet in pattern (a) and near the centers in pattern (e). These figures also indicate that the deviation of the ZMP in pattern (a) was small when compared with that of pattern (e), particularly on a high-friction floor.

The average deviation of the rotational center is shown in Fig. 14. The deviation in pattern (a) is smaller than that in pattern (e). It could be said that the load distribution control contributed toward the reduction in the deviation of the shuffling movement. The floor friction also affected the rotational center, and the friction coefficient had a considerable effect on the shuffle turning. These results are contrary to the results of a previous study.[7]

In order to confirm the versatility of shuffle turning control, we conducted experiments on the patterns shown in Fig. 5, the results of which are presented in Fig. 15. In these figures, the circles and X-marks indicate the initial positions of the rotational center of the feet. The blue and green squares represent the measured positions of the rotational center after turning. The robot performed the task, as intended in each of the experiments, which confirmed the versatility of our shuffle turning method.

7. Conclusion

We proposed a shuffle turning method for a humanoid robot by controlling the load distribution of each sole. In this method, the angle of the feet is controlled and the load is concentrated onto a certain point of the soles. In order to verify the proposed method, we conducted experiments comparing two kinds of load distribution and two kinds of floor material with different friction coefficients. The results show that a load distribution is necessary for a correct shuffle turning motion. In addition, the results reveal that friction has a considerable effect on shuffle turning.

A future research topic will be to control the load distribution of the soles dynamically depending on the situation, and to evaluate the stability through a comparison with conventional turning methods.

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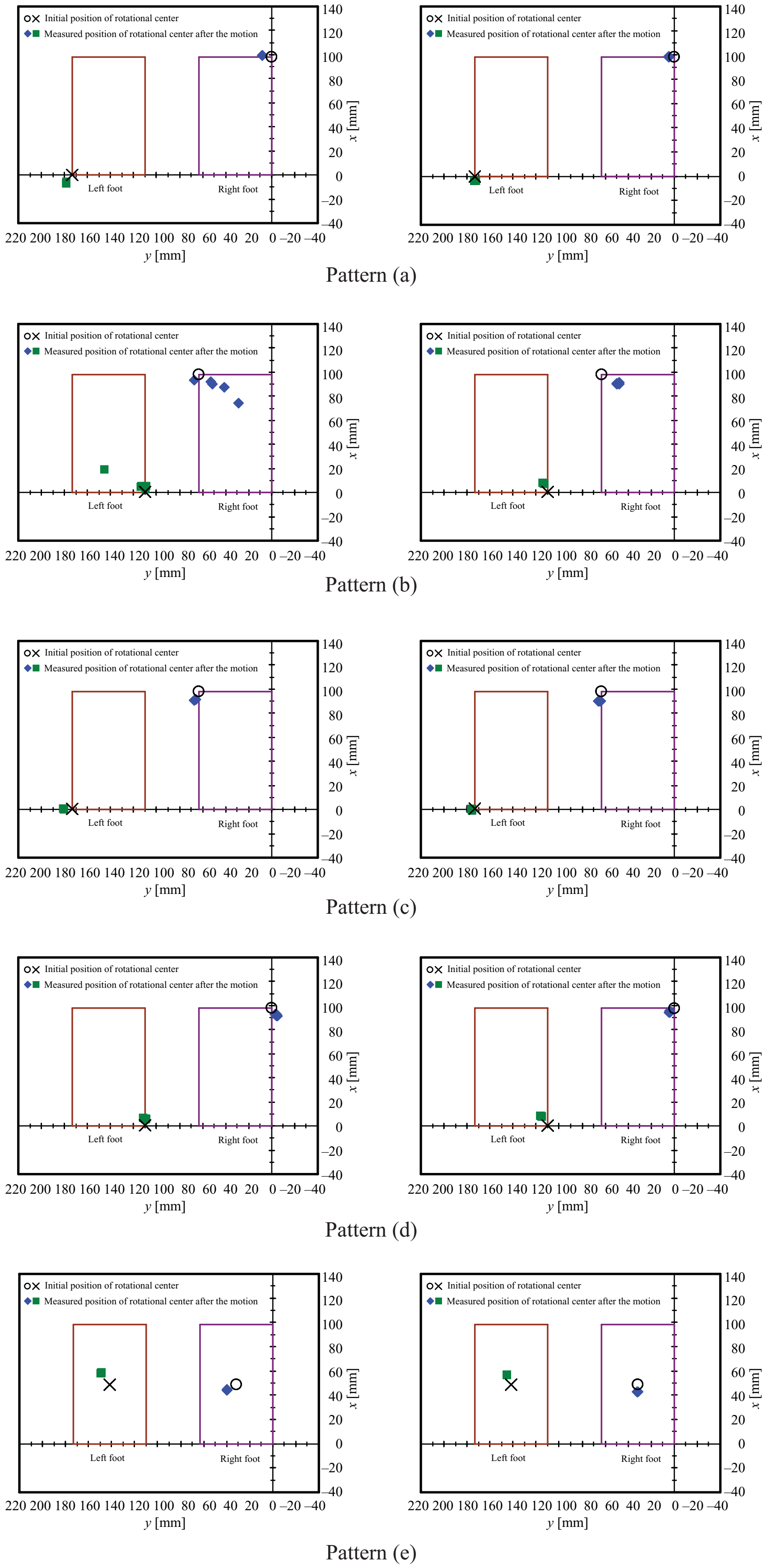

Fig. 15. Deviation of rotational center (left: on a low-friction floor; right: on a high-friction floor).

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