Running Gait Generation for Biped Robot

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ABSTRACT

An attempt to increase the running speed of a biped robot often results in a loss of balance due to slip and spin generated just before lifting or after landing its foot. In order to solve this issue, we developed the gait generation technology that assures dynamic stability while suppressing slip and spin by defining the allowable range of friction force between a sole and a floor. The range of the friction force changes according to the vertical ground reaction force, and is used to adjust the horizontal acceleration, bend, and twist of the robot's torso. By adjusting the range of the friction force, a uniform approach can be taken to generate various gaits such as walking on a floor with low friction coefficient, or slow jogging. Slow jogging is an intermediate motion between walking and running in which the vertical ground reaction force does not quite reach zero. The gait generation technology realizes a running speed of 10 km/h in an experimental robot of the same size as ASIMO.

1. Introduction

Honda is engaging in research on humanoid robots that bring new value by coexisting and collaborating with people, and by providing a useful function in society[(1)-(3)]. Research on running is crucial to the mobility of such robots in order for them to be able to move rapidly to keep up with the movement of people and respond agilely when a person appears suddenly in front of them.

Running allows a longer stride than walking because it involves forward movement above the ground. Consequently, running is advantageous for rapid movement. Running also generates a vertical ground reaction force of about twice the body weight in the vicinity of the lowest point in the vertical movement of the torso. This raises the limit of the ground friction force, thus enabling sudden acceleration and facilitating a more agile response to changing conditions.

In 2004, Honda announced that ASIMO was able to run in a straight line at 3 km/h, and in 2005, that it was able to run in a straight line at 6 km/h and in a circular pattern at 5 km/h [Figs. 1(a) and (b)][(3)]. Continuing research subsequently yielded an experimental robot the same size as ASIMO that is able to run at 10 km/h. This paper describes the gait generation technology that was at the core of these running achievements.

(a) Running (6 km/h)

(b) Running in circular pattern (5 km/h)

Fig. 1 Running posture of ASIMO

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2. ZMP-criteria Gait Generation

One of the general methods for biped robot walking control is to generate a desired gait and make the actual robot follow that gait. Honda robots also make use of this method. The desired gait is defined in terms of the trajectory of the foot position and posture and the trajectory of the torso position and posture, which are needed to determine the robot's joint angles. Providing dynamic stability is crucial to generating the desired gait.

The concept of the zero moment point (ZMP) has been proposed as an approach to providing this stability[4]. The resultant force of the gravity and the inertial force generated by the robot moving is called the total inertial force. The point on the floor at which the moment (strictly speaking, this excludes the component of rotation around the vertical axis) created by that total inertial force becomes zero is the ZMP (Fig. 2). In order for the robot to be dynamically stable, the ZMP should be within the ground contact area of the supporting leg [the region with slanted lines in Fig. 3(a)] during a single support phase, and within the ground contact envelope of the two legs [the region with slanted lines in Fig. 3(b)] during a double support phase. When the ZMP departs from these bounds, then the robot cannot necessarily be provided ground contact and it may fall over.

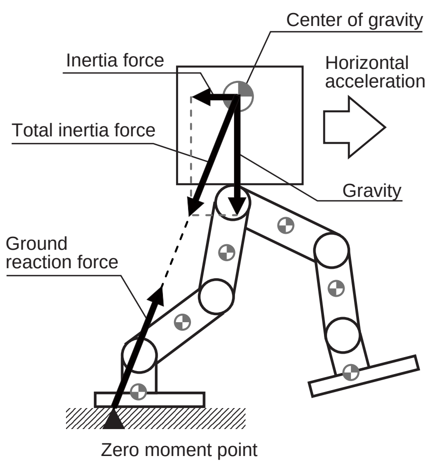
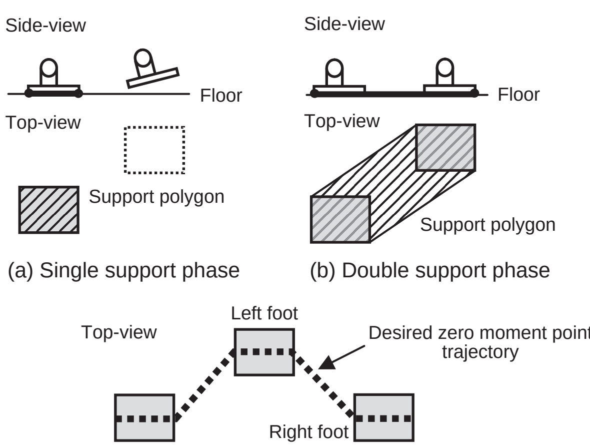


Fig. 2 Zero Moment Point (ZMP)



(a) Single support phase (b) Double support phase

(c) Desired zero moment point trajectory

Fig. 3 Desired zero moment point trajectory

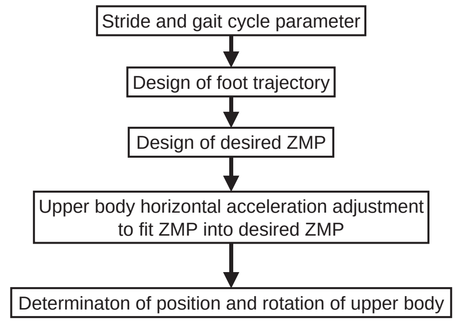
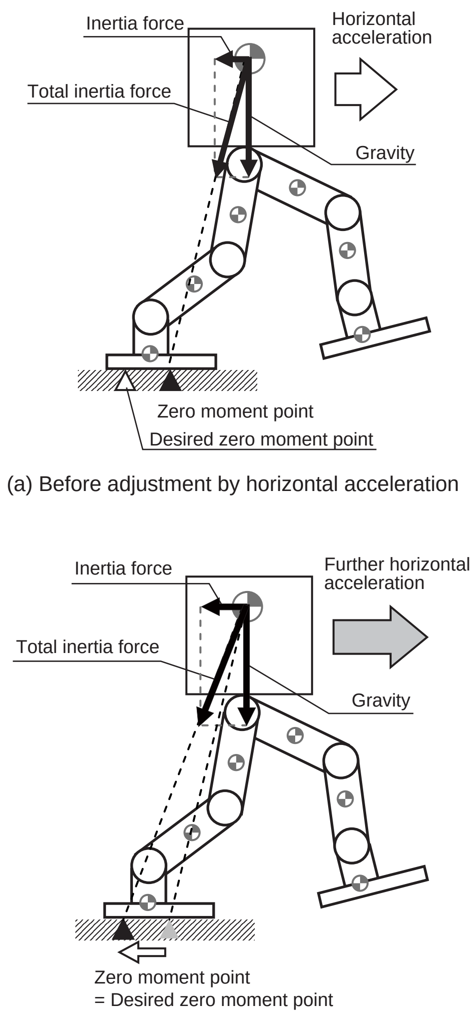


Fig. 4 Flow of ZMP based walking gait determination



(a) Before adjustment by horizontal acceleration

(b) Adjustment by horizontal acceleration

Fig. 5 Balancing motion via upper body horizontal acceleration

The ZMP-criteria gait generation method sets the trajectory of the desired ZMP to satisfy the above conditions, and generates the desired gait so that it will realize that trajectory. This method (Fig. 4) involves first setting parameters such as stride and gait cycle. These parameters then provide the basis for determining the foot trajectory. Next the desired ZMP trajectory is set within the range of stability. Specifically, the desired ZMP trajectory is set so that, from the instant when the foot stepping forward (the leading foot) touches the floor to the instant when the trailing foot lifts up, it moves from the toe of the trailing foot to the heel of the leading foot, and during the single support phase, the trajectory moves from the heel to the toe of the foot [Fig. 3(c)].

Horizontal acceleration of the torso of the robot is defined so that ZMP calculated from the robot's movement agrees with the desired ZMP. This is to make the moment generated by the total inertial force around the desired ZMP equal to zero. As shown in Fig. 5(a), for example, when the ZMP calculated from movement locates farther forward than the desired ZMP, the robot's torso position is accelerated further forward. Then the ZMP calculated from movement shifts toward the rear so that the moment around the desired ZMP will be zero [Fig. 5(b)].

Finally, the horizontal acceleration of the torso is doubly integrated to obtain the horizontal position of the torso. The torso posture is kept in a predetermined posture (an upright posture, for example). This method will generate a gait that provides stability.

In this method of ZMP-criteria gait generation, the horizontal acceleration of the center of gravity is determined dependently. The horizontal ground reaction force is also determined dependently.

3. Issues with Previous Technology

Generation of a running gait necessitates generation of movement for which the ground reaction force is zero when the robot is above the ground. Therefore, the ZMP-criteria gait generation method, in which the ground reaction force is determined dependently, cannot be applied to generation of a running gait.

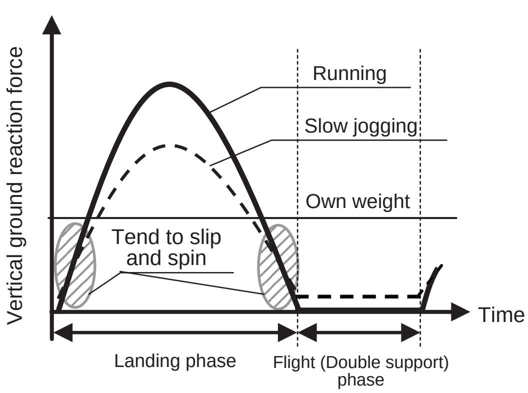


Fig. 6 Vertical ground reaction force of running and slow jogging

To address this issue, a method has been proposed that will generate the gait while switching the movement constraint conditions at the boundary between the flight phase when the robot is above the ground and the landing phase when it is in contact with the ground[5]. During the flight phase, the robot's position and posture will be determined such that the movement of the center of gravity describes a parabola while the angular momentum around the center of gravity is conserved. Meanwhile, during the landing phase, the robot's position and posture are determined by the ZMP-criteria gait generation method.

Use of this method allows the generation of a gait in which the ground reaction force will be zero during the flight phase. During the period just before lifting or after landing its foot, however, when the vertical ground reaction force is small (the slanted part of the line in Fig. 6), the dependently determined horizontal ground reaction force exceeds the limit for the ground friction force, so there is a possibility that the robot will slip or spin. Slip can cause the robot to fall over to the front or back. Spin can not only reduce the rectilinearity of the robot's movement, but it can cause deviation of the landing position, and it can also generate a large centrifugal force when the robot is running fast, making the robot fall over laterally.

In the case of slow jogging, at least one of the feet is always in contact with the ground. Therefore, the vertical ground reaction force is not zero and there is no period when the robot is above the ground. The switching method cannot be applied in such a case. On the other hand, use of the ZMP-criteria gait generation method throughout will leave open the possibility of a fall due to slip or spin even during the double support phase, when the vertical ground reaction force is small (Fig. 6).

4. Running Gait Generation

In order to address the issue described in the previous section, a method was developed to set the allowable range of the friction force, which changes continuously with the changing vertical ground reaction force, and, on that basis, to generate a gait that will suppress slip and spin. This method can provide dynamic stability just before the robot lifts or after it lands its foot. The method is also capable of uniform gait generation for movement that is in between walking and running, and for walking on a floor with a low friction coefficient. This gait generation method is introduced below.

4.1. Torso Trajectory Generation Taking the Horizontal Ground Reaction Force into Consideration

The desired ZMP trajectory during the landing phase is set using a method similar to that for ZMP-criteria gait generation. No ground reaction force is generated during the flight phase, so that the total inertial force becomes zero, and the moment around arbitrary action point becomes zero. As a result, movement unrelated to the desired ZMP is generated. The desired ZMP can therefore be placed in an arbitrary location, but it is set to move continuously to the next landing position in order to provide continuity with the landing phase.

Figure 7 shows the flow for generating the trajectory of the torso position and posture (excluding the component of rotation around the vertical axis) when running. First, the pattern of the vertical ground reaction force is designed according to the duration of the flight phase, the duration of the landing phase, and the desired height of the center of gravity at the instant when the robot lands on the ground (Fig. 8). Next, the allowable range for the horizontal ground reaction force is set according to this vertical ground reaction force (fine line in Fig. 9).

The horizontal acceleration of the torso for the desired gait is adjusted so that the moment around the desired ZMP will be zero, as was done for the walking gait. The horizontal ground reaction force is obtained dependently by this adjustment (dotted line in Fig. 9). If this horizontal ground reaction force is within the allowable range, this adjusted torso trajectory provides both dynamic stability and suppression of slip. If it is not, then the horizontal acceleration of the torso is limited so that the horizontal ground reaction force will come within the allowable range (heavy line in Fig. 9). This limitation, however, means that the conditions for dynamic stability, in which the moment around the desired ZMP is zero, are no longer satisfied. Dynamic stability is therefore satisfied by modifying the rate of change of the angular momentum around the center of gravity of the robot (Fig. 10). This is done by making the torso rotate (bend) while keeping the horizontal component of the acceleration of the center of gravity of the robot unchanged. This rotation of the torso has the same effect as displacing the action point of the total inertial force, so that the moment around the ZMP can be made zero.

The adjustment of the horizontal acceleration of the torso together with the compensation by the rotation of the torso satisfy the conditions for dynamic stability. However, the compensation that is brought about by rotating the torso modifies the rotational acceleration of the torso because of the limit on the horizontal ground reaction force. Consequently, the torso posture ends up diverging because of the time integral. The torso of an

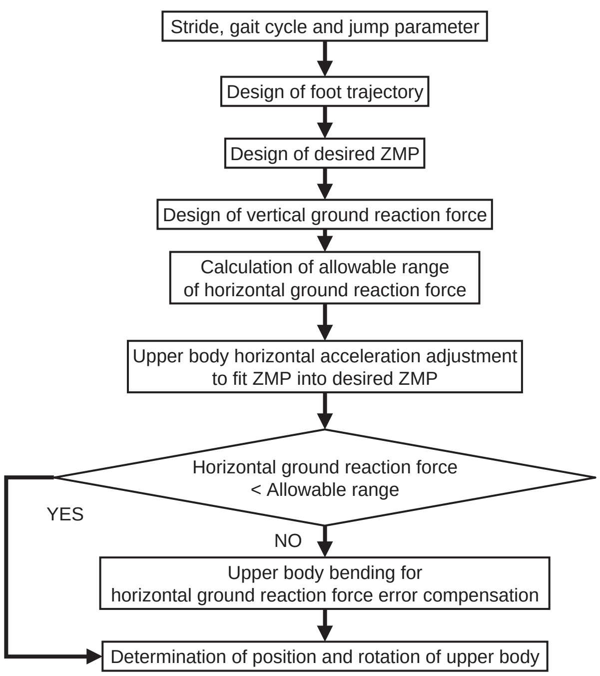


Fig. 7 Flow of running gait determination

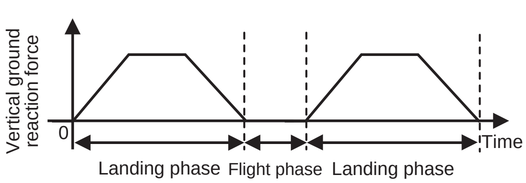


Fig. 8 Vertical ground reaction force

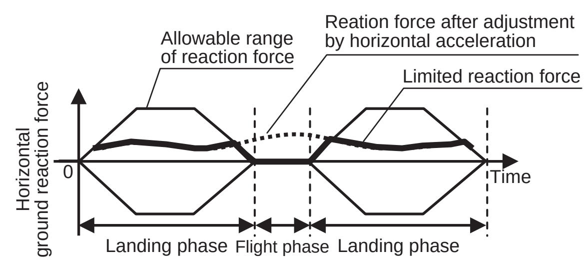


Fig. 9 Distribution of horizontal force

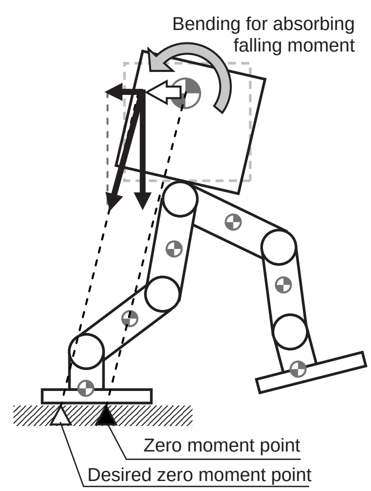


Fig. 10 Balancing motion via upper body bending

actual robot cannot be rotated endlessly, so this becomes an unrealizable gait. The torso posture is therefore recovered while the vertical ground reaction force is large.

4.2. Generation of the Trajectory of Rotation by the Torso around the Vertical Axis

When the yaw moment of the ground reaction force exceeds the moment limit of the ground friction force, a spin is generated. This yaw moment becomes large when the robot moves its legs forward at high speed, such as when running or walking fast. As noted earlier, dynamic balance is lost when spin is generated, increasing the possibility that the robot will fall over. In order to help prevent this, the allowable range of the yaw moment is set according to the vertical ground reaction force and friction coefficient between a sole and a floor (Fig. 11). When the yaw moment exceeds the allowable range, compensation is applied by the torso rotating around the vertical axis (twist) (Fig. 12), providing dynamic stability around the vertical axis. However, a modification is applied to the rotational acceleration of the torso around its vertical axis, so that the angle of rotation (twist angle) of the torso around its vertical axis ends up diverging because of the time integral, just as in the generation of the torso position and posture trajectory in the previous section. Therefore, the rotation of the torso around the vertical axis is recovered at a time when the vertical ground reaction force is large.

The method described in this section is able to provide dynamic stability just before lifting or after landing the foot. It is also capable of generating a uniform gait just by changing the allowable range of ground friction force, even during slow jogging, without switching the movement constraint conditions. This method can also generate a gait that suppresses slip, even on a floor with a low friction coefficient, just by reducing the allowable range of the ground friction force.

5. Gait Generation Results

Computer simulation of a robot with the same leg length as ASIMO was used to generate the desired gait for running at 10 km/h. The stride was set at 730 mm and

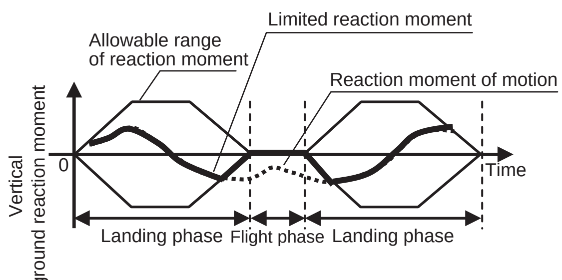


Fig. 11 Limit of vertical ground reaction moment

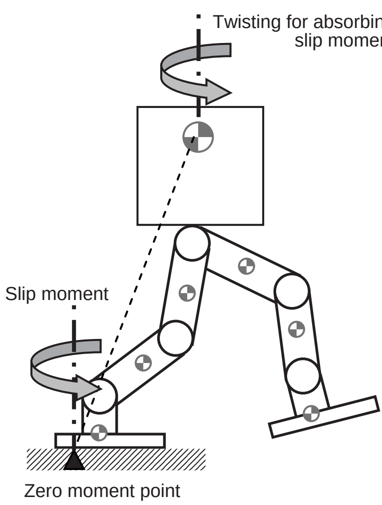


Fig. 12 Vertical moment control

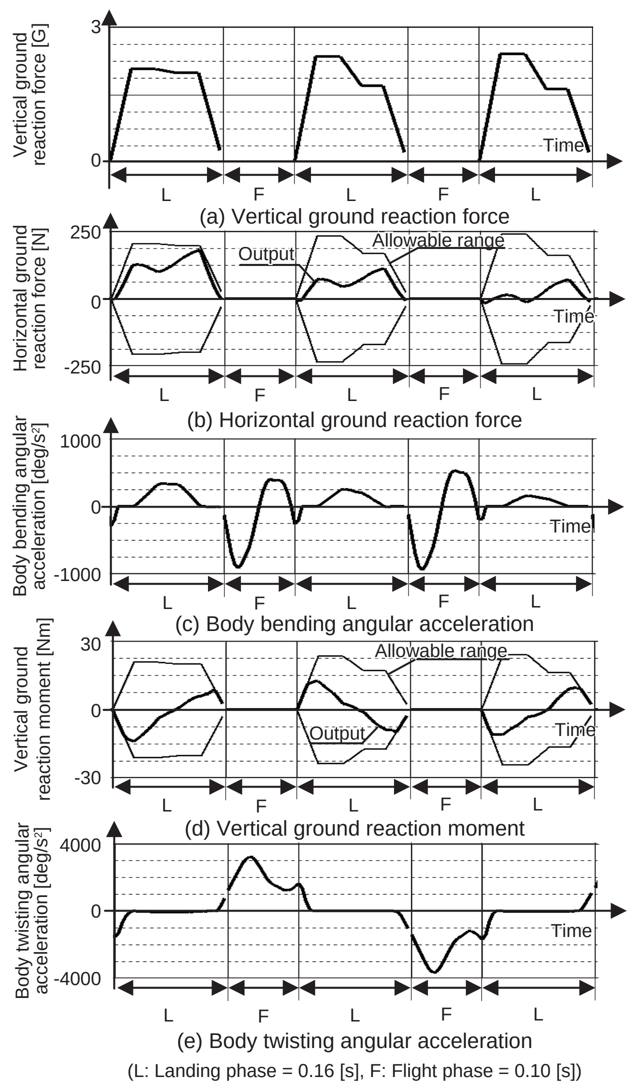


Fig. 13 Force and moment design at 10 km/h running

the gait cycle at 0.26 s (0.10 s during the flight phase, 0.16 s during the landing phase). Figure 13 shows the design value for vertical ground reaction force when running (a), the allowable range for the horizontal ground reaction force [fine line in (b)] and horizontal ground reaction force in the generated gait [heavy line in (b)], the angular acceleration of the bending of the torso (c), the allowable range for the yaw moment [fine line in (d)] and yaw moment of the generated gait [heavy line in (d)], and the angular acceleration of the twisting of the torso (e). The first landing phase in these graphs occurs in a state of accelerated running, and the subsequent two landing phases occur in the state of constant running at 10 km/h.

As shown in Figs. 13(b) and (c), the horizontal ground reaction force in the generated gait comes within the allowable range. An angular acceleration that compensates for the excess portion is generated during the flight phase and in its vicinity, in which the allowable range is reduced, and an angular acceleration for recovery is generated during the landing phase.

As shown in Figs. 13 (d) and (e), the yaw moment of the generated gait also comes within the allowable range. An angular acceleration that compensates for the excess portion is generated during the flight phase and in its vicinity, in which the allowable range is reduced. This angular acceleration is generated alternately to the left and to the right, each canceling out the other, so that the angular acceleration for recovery becomes more or less zero.

The above results indicate that this method is able to generate gaits that provide dynamic stability while also suppressing slip and spin just before the robot lifts or after it lands its foot.

6. Running Experiment

An experiment in running at 10 km/h was conducted using a robot with legs that are the same length as ASIMO's but lighter in weight, and actuators with enhanced output. The robot was controlled so as to follow the desired gait generated in section 5.

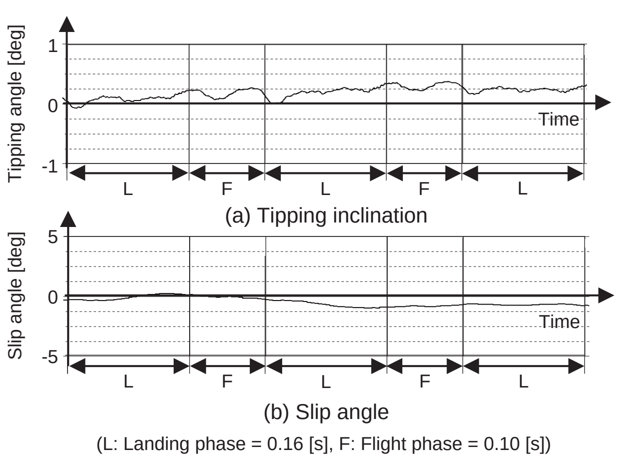


Fig. 14 Inclination error at 10 km/h running

With an actual robot, a tracking error occurs with respect to the desired gait because of the influence of actuator tracking capability, mechanical deflection, and other such factors. The desired gait therefore does not obtain the necessary ground reaction force, dynamic balance is lost, and the robot tips over. As this leaning is likely to result in the robot falling over, ground reaction force control (so-called compliance control)[1,2] was exercised during the landing phase so as to generate the necessary ground reaction force. In addition, a ground reaction force moment according to the inclination of the robot was generated around the desired ZMP during the landing phase to stabilize the robot's posture. Meanwhile, the robot's posture during the flight phase was stabilized using the reaction from the torso rotating around the center of gravity[3]. Figure 14(a) shows the tipping angle of the robot while Fig. 14(b) shows the spin angle at that time. The tipping angle is an estimated value from a gyrosensor and acceleration sensor. The tipping angle is held to within ±0.4 deg while the spin is held to within ±1 deg. It is apparent that stable running was achieved with no deterioration of behavior due to slip and spin just before the robot lifted or after it landed its foot.

7. Conclusion

Gait generation technology for a biped robot was developed that sets a continuously changing allowable range for the friction force between a sole and a floor according to the vertical ground reaction force. In order not to exceed this allowable range, the method adjusts the horizontal acceleration and bending and twisting of the torso. This technology makes available a method for providing dynamic stability during running while suppressing the slip and spin of the robot just before lifting or after landing its foot. The technology can be applied in a uniform manner just by changing the allowable range of the ground friction force for various patterns of walking, including slow jogging and other forms of intermediate movement between running and walking in which the vertical ground reaction force does not completely reach zero, as well as for when walking on a floor with a low friction coefficient.

By use of this technology, running at a speed of 10 km/h was achieved in an experimental robot the same size as ASIMO.

For the future, this technology will be used as a basis for further enhancement of movement capabilities. The goal is the realization of a robot that is able to respond in an agile manner when people appear suddenly in front of it, so that the robot can coexist and collaborate with people and fulfill a useful function in society.

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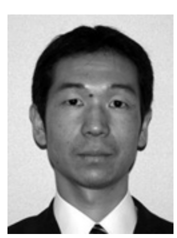

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