Stability Criterion for Humanoid Running[1)]

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Abstract A humanoid robot has high mobility but possibly risks of tipping over. Until now, one main topic on humanoid robots is to study the walking stability; the issue of the running stability has rarely been investigated. The running is different from the walking, and is more difficult to maintain its dynamic stability. The objective of this paper is to study the stability criterion for humanoid running based on the whole dynamics. First, the cycle and the dynamics of running are analyzed. Then, the stability criterion of humanoid running is presented. Finally, the effectiveness of the proposed stability criterion is illustrated by a dynamic simulation example using a dynamic analysis and design system (DADS).

Key words Humanoid robot, running, stability criterion

1 Introduction

In increasingly elderly societies, the possibility and need of robots to assist human activities in human daily environments such as offices, homes and hospitals is growing rapidly. Our daily environments are constructed for humans, a humanoid robot with the anthropoid shape (a head, two arms and two legs) is an appropriate form to adapt to human daily environments. In addition, humanoid robots have better mobility than conventional robots, especially when stepping in rough terrain, steep stairs and obstacle environments.

The humanoid robot has been a research focus of robotics. Previous investigations mainly concerned the stable and reliable biped walking. Vukobratovic[1] originally proposed the dynamic stability criterion of ZMP (zero moment point) as the point in the ground plane about which the total moments due to ground contacts becomes zero in the plane. To provide precise analysis of walking stability, some stability concepts were discussed such as FRI (foot rotation indicator)[2] and valid stable region[3]. In order for humanoid robots to realize stable walking, many researchers have proposed various methods of the pattern generation such as off-line pattern generation[4∼7], online pattern generation[8,9], and real-time sensor control[6,10∼13].

On the other hand, some researchers have studied running robots and focused on hopping robots. Matsuoka[14] proposed the mechanism of hopping robots; Raibert[15,16] realized various motions such as somersaults using a real hopping robot driven by pneumatic and hydraulic actuators. Raibert′s work, running robots have been widely studied such as monopod, bipedal, quadruped and hexapod running robots[17∼22]. However, the mechanism of these running robots is different from that of the biped humanoid robots.

Humanoid running involves the dynamics of multiple bodies. Comparing with the above-mentioned running robots, the humanoid running is more complicated. Hodgins[23] discussed the kinematics simulation of a simulated runner with computer animation. Kwon[24] derived the humanoid hip trajectory using a simple model of humanoid robots and two feet trajectories using the conservation law of the angular momentum. Kajita[25,26] proposed a method to generate a running pattern using the dynamics of an inverted pendulum, and developed a control method based on total linear/angular momentum of the multi-link system. These investigations concerned the humanoid running based on simplified models such as the inverted pendulum, while the dynamic stability of humanoid running based on the whole dynamics of the humanoid robot has not been sufficiently discussed so far.

2 Running cycle

A walking cycle can be divided into a double-support phase and a single-support phase, and there always is a foot contacting the ground. The running cycle is different from the walking cycle. There is a phase that no foot contacts the ground. A running cycle can be divided into a single-support phase and a flight phase (Fig. 1). In the single-support phase, one foot is stationary contacting the ground, and the other foot is swinging in the air and relatively passing from the rear to the front. In the flight phase, the body flies in the air, and no foot is in contact with the ground. The phase begins with the toe of the rear foot to take off the ground, and ends with the toe of the forward foot to touch the ground.

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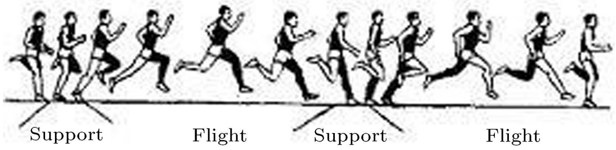


Fig. 1 Running cycle

At the beginning of the single-support phase, that is, at the moment when one foot touches the ground, the ground projection of the center of gravity (CoG) is on the back of the supporting heel. On the other hand, at the end of the single- support phase, that is, at the moment when the body takes off the ground, the ground projection of the CoG is the front of the supporting toe. In the flight phase, only the gravitational force acts on the body, and the body moves like a projectile in the air.

3 Stability criterion of humanoid running

The humanoid robot is modeled as a rigid body system consisting of n links including a head, two arms, two legs and a trunk. According to the specialties of running, the stability criterion of humanoid running is discussed in two cases: the support phase and the flight phase.

3.1 Support phase

During the support phase, to maintain the robot′s dynamic equilibrium, the ground reaction force $\vec{R}$, and the moment $\vec{M}$, should act at an appropriate point P that is within the foot support area to balance all the other forces acting on the robot such as the gravitational force $\vec{G}$, the inertial force $\vec{F}$ and the corresponding moments, as shown in Fig. 2.

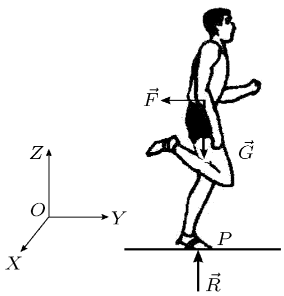


Fig. 2 Single-support phase

The ground reaction moment can be decomposed into the vertical and horizontal components with respect to the reference frame. The vertical reaction moment represents the moment of the friction reaction forces reduced at point P. Assuming that the foot/ground friction is sufficiently large and there is no sliding, the friction forces can balance the vertical reaction moment. The horizontal reaction moment represents the moment of the dynamic reaction forces that are not compensated by the friction forces.

The equations of the dynamic equilibrium are given according to D′Alembert principle in the reference coordinate system during the support phase as follows:

$$\sum_{i=1}^{n} m_i \times \vec{g} + \sum_{i=1}^{n} m_i \times \vec{a}_i + \vec{R} = 0, \quad \overrightarrow{op} \times \vec{R} + \sum_{i=1}^{n} \overrightarrow{oc}_i \times m_i \times (\vec{g} + \vec{a}_i) + \sum_{i=1}^{n} \vec{H}_i + \vec{M} = 0 \tag{1,2}$$

where o denotes the origin of the reference frame (Fig. 2), n is the total of body links. m_i is the mass, c_i is the center of mass (CoM), $\vec{a}_i$ is the linear acceleration, $\vec{H}_i$ is the angular momentum about CoM, of the i-th link.

Substituting the following relation

$$\overrightarrow{oc}_i = \overrightarrow{op} + \overrightarrow{pc}_i \tag{3}$$

and (1) into (2) gives

$$\sum_{i=1}^{n} \overrightarrow{pc}_i \times m_i \times (\vec{g} + \vec{a}_i) + \sum_{i=1}^{n} \vec{H}_i + \vec{M} = 0 \tag{4}$$

The horizontal components of the ground reaction moment $\vec{M}$ is equal to zero because the ground reaction moment acts at point P. Considering only the dynamic moment equilibrium in the horizontal ground plane, (4) can be written as

$$\left(\sum_{i=1}^{n} \overrightarrow{pc}_i \times m_i \times (\vec{g} + \vec{a}_i) + \sum_{i=1}^{n} \vec{H}_i \right)_h = 0 \tag{5}$$

where the subscript implies the horizontal components.

(5) represents the mathematical interpretation of point P and provides the formalism for computing the coordinates of point P in the horizontal ground plane. (5) is identical to the dynamic moment equilibrium of ZMP in comparison with them. So the appropriate point P in the support area that meets the humanoid robot′s dynamic equilibrium is ZMP[1].

3.2 Flight phase

In this phase, the humanoid robot flies in the air with no foot contacting the ground at all. The gravitational force acts on the robot at the CoG, and the humanoid robot′s trajectory is a parabolic curve. The dynamics equations are as follows.

$$\sum_{i=1}^{n} m_i \times \vec{g} + \sum_{i=1}^{n} \times \vec{a}_i = 0, \quad \sum_{i=1}^{n} \overrightarrow{cc}_i \times m_i \times (\vec{g} + \vec{a}_i) + \sum_{i=1}^{n} \vec{\dot{H}}_i = \vec{A} \tag{6,7}$$

where c is the CoG, $\vec{A}$ is the total moment about the CoG of the humanoid robot. The resultant moment about the CoG exerted by the gravitational force and the inertial force is equal to zero. So the total moment is

$$\sum_{i=1}^{n} \vec{\dot{H}}_i = \vec{A} \tag{8}$$

Supposing that the period of one running step is T, the time of the kth step running is from kT to $(k+1)T, k = 1, 2, \cdots$. T_s denotes the interval of the support phase, and T_f denotes the interval of the flight phase, so

$$T_s + T_f = T \tag{9}$$

The following equation is obtained:

$$\int_{kT+T_s}^{kT+T} \sum_{i=1}^{n} \vec{\dot{H}}_i \mathrm{d}t = \int_{kT+T_s}^{kT+T} \vec{A} \mathrm{d}t \tag{10}$$

Assuming there is no disturbance acts on the humanoid robot when the robot is flying. Using the conservation law of the angular momentum:

$$\sum_{i=1}^{n} \vec{H}_i(t) = C, \quad t \in [kT + T_s, kT + T] \tag{11}$$

where C is a constant. Namely, the total angular momentum about its CoG is constant in the flight phase. That is

$$\sum_{i=1}^{n} \vec{H}_i(kT + T_s) = c \tag{12}$$

If C is not equal to zero, it will happen that the humanoid robot rotates around its CoG in the air, and there must be a moment that makes the robot rotate. The rotating moment takes its effect only at the moment when the robot takes off. So

$$\sum_{i=1}^{n} \vec{H}_i(kT + T_s) = \int_0^{T_1} \vec{A}(kT + T_s) \mathrm{d}t \tag{13}$$

T_1 is the time slice that the moment $\vec{A}(kT + T_s)$ acts.

In order to make the humanoid robot fly stably in the air and continue running forward when the humanoid robot touches the ground, the total angular momentum about its CoG at the moment when the robot is jumping from the ground will be controlled in a certain scope.

$$\left| \sum_{i=1}^{n} \vec{H}_i(kT + T_s) \right| \leqslant \varepsilon \tag{14}$$

where ε is a non-negative number. If the total angular momentum is beyond the certain scope, the stability of the humanoid robot will be broken away. It results in that the humanoid robot cannot contact the ground stably and has risk of falling, thus the humanoid robot cannot continue to run.

Particularly, if the total angular momentum about its CoG when takeoff is equal to zero, *i.e.*,

$$\sum_{i=1}^{n} \vec{H}_i(kT + T_s) = 0 \tag{15}$$

Namely, the humanoid robot will maintain a fixed posture in the flight phase, then the following equation can be obtained:

$$\vec{A}(kT + T_s) = 0 \tag{16}$$

that means the total moment about its CoG is equal to zero at the moment when the humanoid robot is taking off the ground.

If the dynamics of the humanoid robot satisfies (14), the humanoid robot is possible to fly in the flight phase. Particularly, if the dynamics of the humanoid robot satisfies (15), the humanoid robot will not rotate about its CoG in the flight phase.

4 Dynamic simulations

4.1 Humanoid model and simulation environment

The humanoid is a system with multiple joints and many degrees of freedom (DOFs). To predict the physical humanoid motion, it is necessary to accurately formulate and solve the kinematic and dynamic equations of the mechanism. The dynamic software package called dynamic analysis and design system (DADS) can automatically formulate the equations of kinematics and dynamics, solve the nonlinear equations, and provide computer graphics output of the simulation results[27].

Using DADS environment, we developed a virtual humanoid robot (Fig. 3) that consists of a head, a trunk, two arms, and two legs, and has 33 DOFs. The head has 3 DOFs. Each upper limb consists of a upper arm, a forearm, and a hand, and has 9 DOFs: 3 DOFs in shoulder joint, 2 in elbow joint, 2 in wrist joint, and 2 in finger joint. Each leg consists of a thigh, a crus and a foot, and has 6 DOFs, 3 in hip joint, 1 in knee joint, and 2 in ankle joint. The parameters of the humanoid robot are set in Table 1.

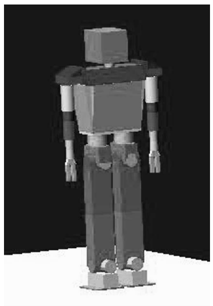


Fig. 3 Humanoid robot in simulator

Table 1 Parameters of the humanoid robot

	head	trunk	arm	thigh	crus	foot
Length (cm)	20	61.5	60	31.5	31.5	13.5
Weight (kg)	1.5	23.5	8.5	9.0	6.0	2.5

4.2 Running trajectories design

If the hip and both feet trajectories are known, all legs joint trajectories of the humanoid robot will be determined by the kinematic constraints. Thus the running trajectories of legs can be obtained uniquely by the trajectories of the hip and both feet. The lateral motion of the hip and both feet can be derived similarly as the sagittal direction. In the following sections, only the trajectories in the sagittal plane are discussed.

Running is a periodic motion. If the trajectories of a period are deigned used the proposed stability criterion of biped running for humanoid robot, the total trajectories of humanoid running can be obtained. For example, if the trajectory of the left foot is designed for a period, and the whole running trajectory of the left foot can be determined, and the right foot trajectory can be obtained at a certain interval, too. The hip trajectory can be designed as well as the foot trajectory.

In the trajectories design, both feet trajectories are specified according to the running speed and running step length at first, then formulate the hip trajectory by 3rd-order spline interpolation using the proposed stability criterion of biped running for humanoid robot (Fig. 4).

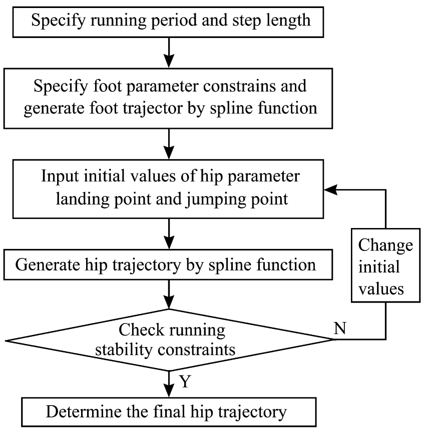
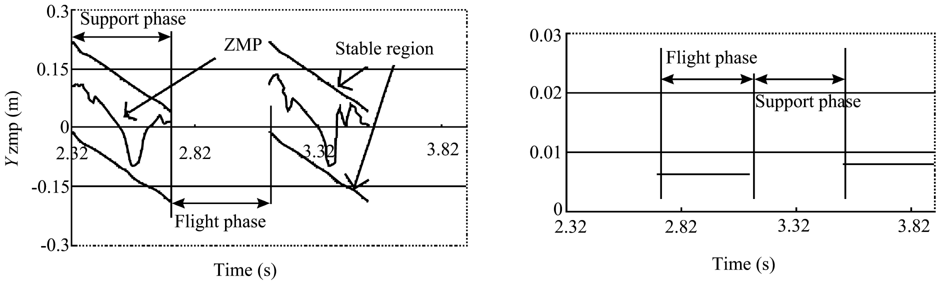


Fig. 4 Algorithm for running trajectories design

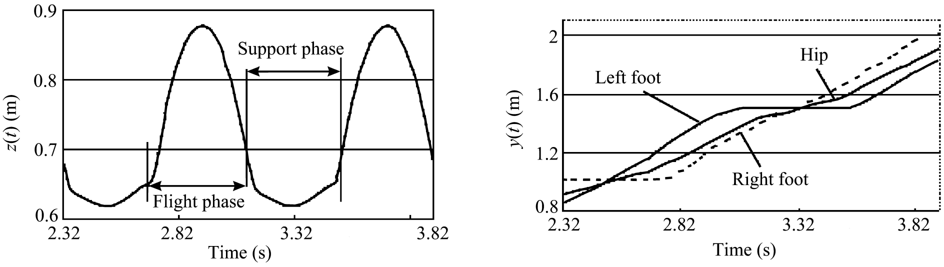
4.3 Simulation results of running

In the running example, it is supposed that the step length is 0.5m, the period of a step is 0.8s, the ground is level, the whole sole is stationary on the ground in the whole support phase. The simulation results are shown in Fig. 5 and Fig. 6.



(a) ZMP trajectory in y-axis (b) Trajectory of the total angular momentum

Fig. 5 Trajectories of ZMP and total angular momentum



(a) Hip motion in z-axis (b) Foot motion and hip motion in y-axis

Fig. 6 Trajectories of foot and hip motion

It is known that the ZMP trajectory (Fig. 5 (a)) is inside the stable region, so the humanoid robot is stable in the single-support phase. The ZMP trajectory does not exist in the flight phase because the humanoid robot flies in the air and no foot contacts the ground. From Fig. 5 (b), the total angular momentum is always not equal to zero in the flight phase, but it is always very close to zero and satisfies (14), so the humanoid robot can maintain its dynamic stability in the flight phase. The trajectory of the humanoid waist (Fig. 6) is smooth either in support phase or in flight phase.

5 Conclusions

The issue of humanoid running stability has rarely been investigated in the previous literature. In this paper, the stability criterion for humanoid running is proposed. The stability constraints based on the whole dynamics for humanoid running are derived. In the support phase, the stability criterion of humanoid running is identical to the ZMP criterion. The dynamics of the humanoid robot must satisfy (14), particularly it satisfies the idealized condition of (16) in the flight phase. Finally, the effectiveness of the proposed stability criterion is illustrated by a dynamic simulation example with DADS.

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