Proceedings of the 2nd International Symposium
on Adaptive Motion of Animals and Machines,
Kyoto, March.4-8, 2003

Simulation study of self-excited walking of a biped mechanism with bent knee

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Abstract

This paper presents a simulation study of a new walking gait of four-link biped model which is self-excited by the hip joint torque proportional to the absolute angle of the swing shank. By holding a bending angle at the knee of the support leg, the biped model can walk faster than the straight support leg model. The influences of the parameters, such as feedback gain, foot radius, mass ratio and the length ratio of the thigh and the shank etc. on the walking speed and stability, are discussed as well.

1. Introduction

It is known that the mobility of legged mechanism is better than wheels in rough terrain because legs can use isolated footholds to optimize support whereas a wheel requires a continuous path of support. This is why so many researchers are concentrated on studying legged machines, especially for biped walking, which is an efficient and sophisticated locomotion. Many control method for stable biped walking are studied. Such as the zero moment point (ZMP) method by Kato [1], the following control of human gait trajectories by Mita [2], the model following control of angular momentum by Sano and Furusho [3], synchronizing control of the swing leg and an inverted pendulum of the support leg by Miyazaki and Arimoto [4], etc..

Recently, the Honda humanoid biped robot, ASIMO [5] is developed. It uses the technology of intelligent real-time flexible walking and is adapted to various circumstances. However, the ASIMO consumes about 1kW at the speed of 1.6km/hr, whereas an adult consumes only 35~93W while walking at a speed of 1.5km/hr~6.6km/hr [6]. Therefore it is necessary to study the biped mechanisms that evoke natural walking in order to improve the efficiency of the biped walking.

We began our research from a simple four-link biped mechanism, which is conceptually similar to McGeer's passive walking machine [7] but has an additional actuator in the hip [8][9]. Based on the self-excitation theory [10], we gave the hip joint of our biped mechanism an input torque proportional to the absolute angle of the swing shank and succeeded to make it walk down a 0.8-degree plane. Because our first biped mechanism only has passive stoppers at the knee joints and the internal knee torque of stance leg is apt to be zero in the case of level ground, it is not robust against external disturbances. And both the knee collision and toe collision are not perfectly the same as in the theoretical model, so an active knee lock mechanism is introduced to prevent the shank from bouncing back and keep the support leg straight. After adjusting the physical parameter values according to the result of simulation, we made a new experimental biped mechanism, which succeeded in walking on a level plain in the same way as simulation [11].

As explained above, legged machine has its advantage to wheeled ones, but it also has its weakness—the speed of legged machine is much lower than wheeled vehicle, especially biped ones. Thus, it's necessary to find the ways of increasing the speed of our biped machine.

This paper aims to find principles of fast biped walking with high efficiency based on self-excitation. Through our understanding of the human walking patterns, we know people always retain some knee flexion during walking [6]. Therefore, we try to apply a bent knee angle to the support leg of our new model in order to make it walk more naturally and fast. In the next section, the analytical model and its basic equations of locomotion will be explained. In section 3, we show the simulated results of stable biped locomotion on level ground focusing on the effect of bent angle. We compare the influence of other parameters such as feedback gain, mass ratio and the length ratio of the thigh and the shank etc., on the walking speed and stability under bent knee walking mode. In order to further speed up the walking, the effect of adding a circular curve foot to the supporting foot is examined as well.

2. The Analytical Model and Basic Equations

Fig.1 shows the biped mechanism that walks with bent knee. The new model looks a little different from our preceding one. We assume that it uses knee brakes instead of the passive stopper and lock mechanism. So the swing leg can be locked at any suitable position. We only consider the biped walking motion in the saggital plane, so the model consists of

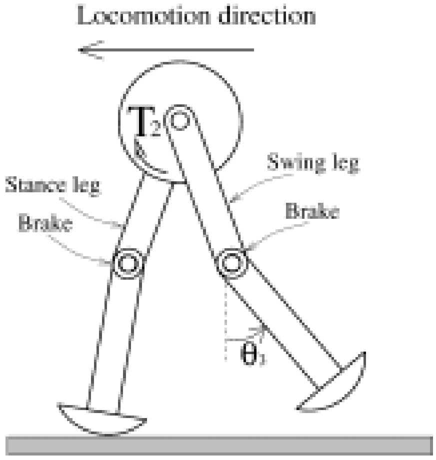


Fig. 1 Three-degree-of-freedom walking mechanism on a sagittal plane

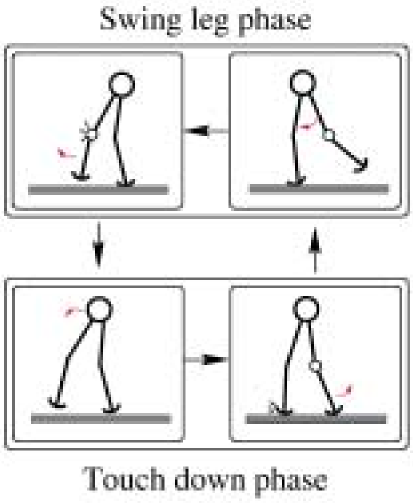


Fig.2 Two phases of biped walking

only two legs and doesn't have a torso. The legs are connected in a series at the hip joint through a motor. Both legs have a thigh and a shank that are connected at the knee joint where a brake is added. We suppose the support leg doesn't extend fully but retains some flexion during the stance phase. So the brake is activated before the swing leg becomes straight and keeps a desired angle between the thigh and the shank. The brake will be released as soon as the stance leg enters the swing phase.

The algorithm of the biped walking is shown in Fig.2, which can be divided into two phases: swing leg phases and touch down phase:

(1) From the start of the swing leg motion to the lock of the knee joint of the swing leg by brake. In this phase, only the brake of support leg is activated.

(2) From the lock of the knee joint of the swing leg to the touch down of the bent swing leg. In this phase, the brakes of both legs are activated.

We assume that the change of the support leg to the swing leg occurs instantly and the friction force produced by the brake is large enough to keep the knee joint locked at a determined angle. There are some necessary rules as follows: the energy dissipated through knee and foot collisions and joint friction should be supplied by the motor, the swing leg should bend at the knee to prevent the tip from touching the ground, and the inverted pendulum motion of the support leg must synchronize with the swing leg motion. In addition, the synchronized motion between the inverted pendulum motion of the support leg and the two-DOF pendulum motion of the swing leg, as well as the balance of the input and the output energy, should have stable characteristics against small deviations from the synchronized motion.

Self-excitation control is applied to the biped model to allow it to perform simple walking on level ground. In our preceding papers, we have shown that a swing leg motion can be autonomously generated by the asymmetrical feedback such as:

$$T_2 = -k\theta_3 \tag{1}$$

It is also known that the damping plays an important role in generating the self-excited motion. So the viscous rotary damper with coefficient γ_3 is applied to the knee joint of the swing leg, which produces a torque as:

$$T_3 = -\gamma_3(\dot{\theta}_3 - \dot{\theta}_2) \tag{2}$$

After the feedback gain k is increased to a certain value, a stable limit cycle of swing leg motion is excited.

Under the assumption of a mechanism with a fixed bent support leg and an unlocked swing leg, the analytical model during the first phase is treated as a three-DOF link system, which is shown in Fig.3. We get the equation of motion in the first phase as:

$$\begin{bmatrix} M1_{11} & M1_{12} & M1_{13} \\ & M1_{22} & M1_{23} \\ sym & & M1_{33} \end{bmatrix} \begin{bmatrix} \ddot{\theta}_1 \\ \ddot{\theta}_2 \\ \ddot{\theta}_3 \end{bmatrix} + \begin{bmatrix} 0 & C1_{12} & C1_{13} \\ -C1_{12} & 0 & C1_{23} \\ -C1_{13} & -C1_{23} & 0 \end{bmatrix} \begin{bmatrix} \dot{\theta}_1^2 \\ \dot{\theta}_2^2 \\ \dot{\theta}_3^2 \end{bmatrix} + \begin{bmatrix} K1_1 \\ K1_2 \\ K1_3 \end{bmatrix} = \begin{bmatrix} -T_2 \\ T_2 - T_3 \\ -T_3 \end{bmatrix} \tag{3}$$

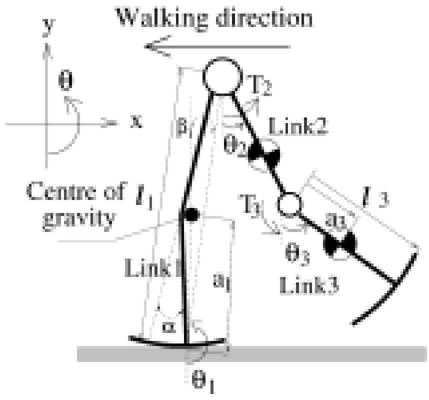


Fig. 3 Analytical model of three degree of freedom walking mechanism

where the elements $M1_{ij}$, $C1_{ij}$ and $K1_i$ of the matrices are shown in Appendix 1. T_2 is the feedback input torque given by Eq.(1) while T_3 is the effect of viscous rotary damper, which is given by Eq.(2).

When the angle between the shank and thigh of the swing leg becomes a certain value, the brake is activated and locks the knee joint. This means the end of the first phase. We assume the knee collision occurs plastically at this time. From the assumption of conservation of momentum and angular momentum before and after the knee collision, angular velocities after the knee collision are calculated from the condition $\dot{\theta}_2^+ = \dot{\theta}_3^+$, and the equation is written as:

$$\begin{bmatrix} \dot{\theta}_1^+ \\ \dot{\theta}_2^+ \\ \dot{\theta}_3^+ \end{bmatrix} = [M]^{-1} \begin{bmatrix} f_1(\theta_1, \dot{\theta}_1^-) \\ f_2(\theta_2, \theta_2^-) - \tau \\ f_3(\theta_3, \theta_3^-) + \tau \end{bmatrix} \qquad (4)$$

where the elements of the matrix $[M]$ are the same as $M1_{ij}$ in Eq.(3). f_1, f_2 and f_3 are presented in Appendix 2. τ is the impulse moment at the knee.

During the second phase, the biped system can be regarded as a two-DOF link system. The basic equation becomes:

$$\begin{bmatrix} M2_{11} & M2_{12} \\ M2_{12} & M2_{22} \end{bmatrix} \begin{bmatrix} \ddot{\theta}_1 \\ \ddot{\theta}_2 \end{bmatrix} + \begin{bmatrix} 0 & C2_{12} \\ -C2_{12} & 0 \end{bmatrix} \begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \end{bmatrix} + \begin{bmatrix} K2_1 \\ K2_2 \end{bmatrix} = 0 \quad (5)$$

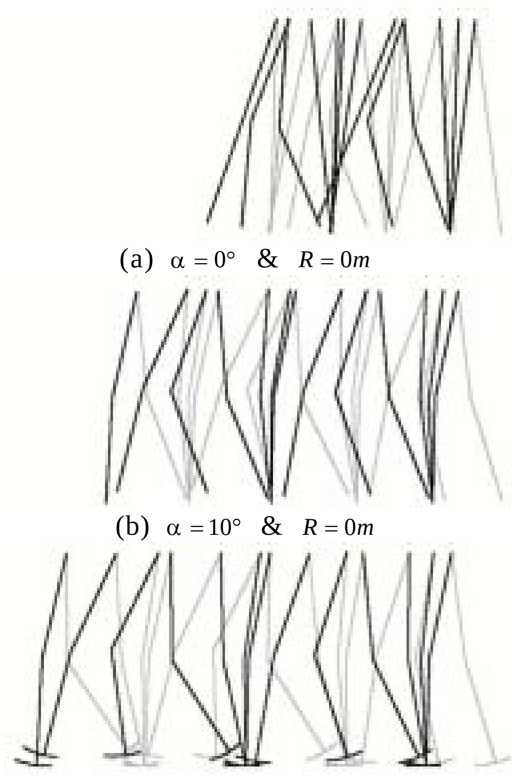
where the elements $M2_{ij}, C2_{ij}$ and $K2_{ij}$ of the matrices are shown in Appendix 3.

We assume that the collision of the swing leg with the ground occurs un-elastically and the friction between the foot and the ground is large enough to prevent slipping. Just like knee collision, the angular velocities of the links after the collision can be derived from conservation laws of momentum and angular momentum. At this time, $\tau = 0$ is put into Eq.4. After the collision, the support leg turn to swing leg immediately and the system enter the first phase again.

3. The Result of Simulation

Table 1. Link parameter values used for simulation study

Parameters	**Thigh**	**Shank**	**Leg**
Length l_i [m]	0.4	0.4	0.8
Mass m_i [kg]	2.0	2.0	4.0
Center of mass a_i [m]	0.2	0.2	0.4
Moment of inertia at mass center I_i [kgm^2]	0.027	0.027	0.21



(a) $\alpha = 0°$ & $R = 0m$

(b) $\alpha = 10°$ & $R = 0m$

(c) $\alpha = 10°$ & $R = 0.3m$

Fig. 4 Stick figure of two walking cycles

The values of the link parameters used in the

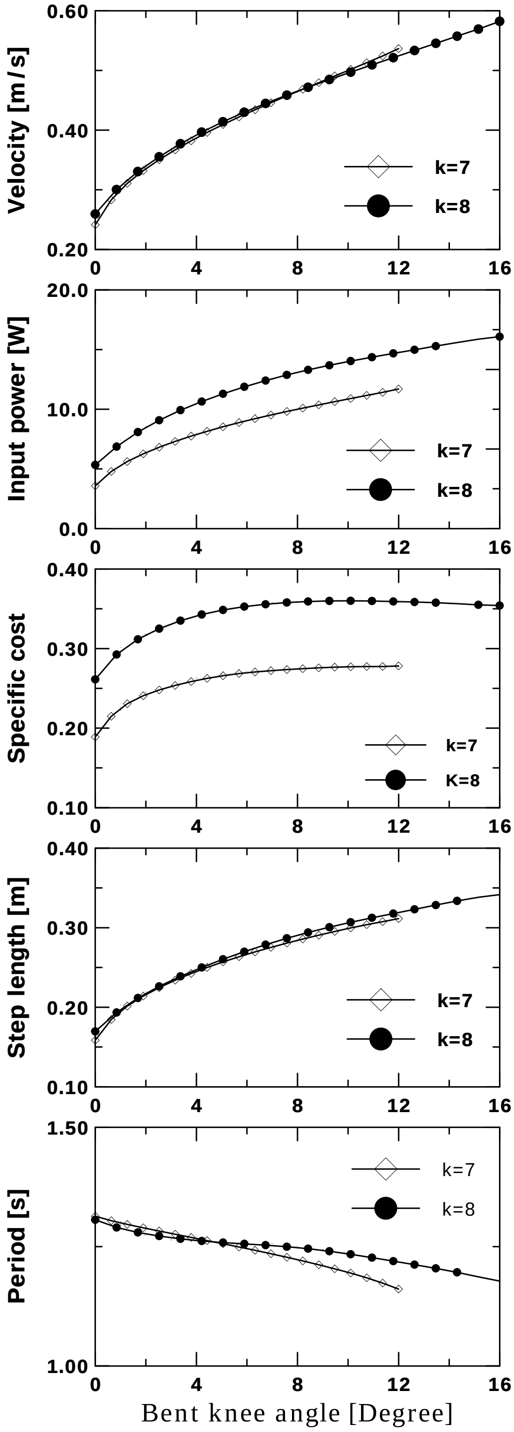


Fig. 5 Effect of bent knee angle

simulation are shown in Table 1. We use the same values as in our preceding paper because it is easy to find the influence of the bent knee angle by comparing the two results. The fourth order Runge-Kutta method is used to solve the basic equations. In order to increase the accuracy, the time step is set to 1ms. In our study of the effect of viscous rotary damper γ_3, it is found that a proper value will give the two linkages of swing leg a maximum angle phase delay. It meets our need to increase the clearance. By considering the efficiency, $\gamma_3 = 0.15$ Nms/rad is used in the simulation.

In the numerical simulation, steady walking locomotion is obtained with the bent knee angles of less than 17 degrees. When the angle is larger than 17 degrees, the step length decreases suddenly and the biped mechanism falls down forward.

Fig.4 illustrates the stick figures of the stable self-excited walking gaits during four steps (two walking cycles) upon the conditions whether the model has the bent knee angle and foot or not. For the convenience of comparing, the feedback gain k is set to be $8 Nm/rad$ in all the cases. In fig.4 (a), it has no bent knee angle and no foot. The step length is 0.18 m and the period of one step is 0.64 s, then the walking velocity is 0.28 m/s. In fig.4 (b), 10 degrees' bent knee angle is added to the support leg. The step length increases to 0.31 m and the period decreases a little, so the velocity is increased to 0.5 m/s. In fig.4 (c), the velocity is increased further to 0.65 m/s by giving the model a foot whose radius is 0.3 m. From the graph, we can find the increase of speed obviously and we also note that the shank motion of the swing leg delays from the thigh motion that yields a marginal clearance (the height of the tip of the swing leg) for the stable walking.

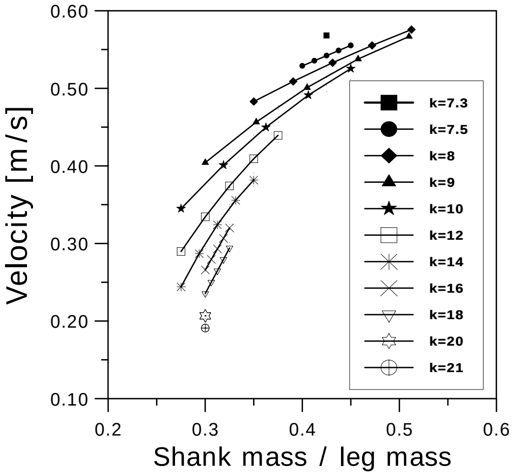
Fig.5 shows the effect of the bent knee angle on the walking velocity, input power, specific cost, step length and period respectively. The average input power is calculated by:

$$P = \frac{1}{t_{end}} \int_0^{t_{end}} \left| \dot{\theta}_2 k \theta_3 \right| dt \qquad (6)$$

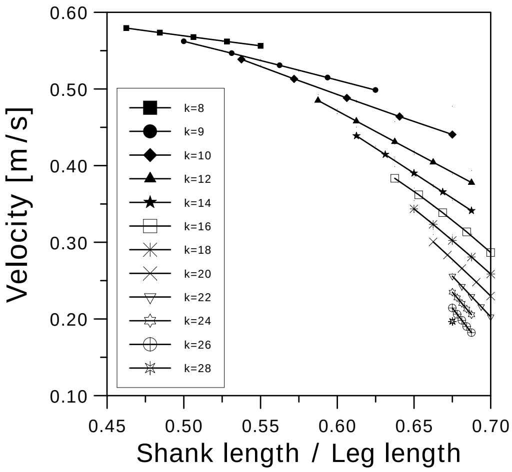
And the specific cost is defined as:

$$E = \frac{P}{mgV} \qquad (7)$$

As the bent angle increases, the center of mass of the swing leg moves toward the hip joint. Therefore, a shorter swing period can be realized. At the same time the center of mass is moved forward in contrast to the straight leg one. Therefore, the support leg rotates forward faster than in the straight leg model because the offset of mass yields the gravity torque to make the support leg rotate in the forward direction. We consider this is the main reason for the increase in step length. With the shorter swing period and the longer step length, a faster walking is realized in the simulation. The result that a larger step length accompanies with a shorter swing period is also in accordance with the way in which these two parameters are related in human walking. However,

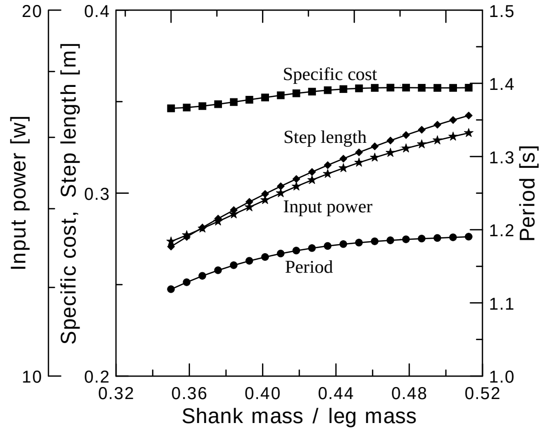


(a) Effect of mass ratio

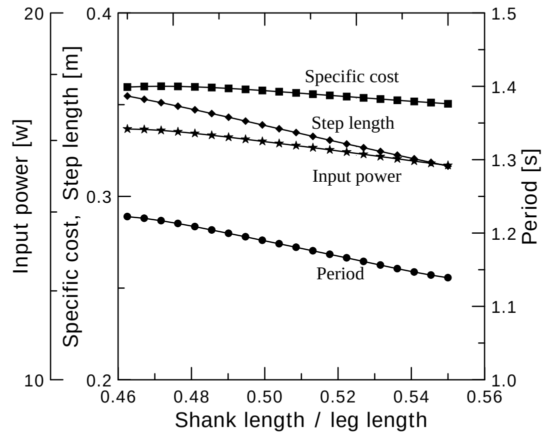


(b) Effect of length ratio

Fig.6 Walkable range of k ($\alpha = 15°$)



(a) Effect of mass ratio



(b) Effect of length ratio

Fig.7 Effect of mass ratio and length ratio on walking characteristics ($\alpha = 15°$ and $k = 8Nm/rad$)

the specific cost increases until bent knee angle α reaches 8 degrees because of the rapid increase of input power. When $\alpha > 8°$ the specific cost stops to increase and even decreases a little because the increase of velocity is faster than the increase of input power. Since the input torque at the hip joint is proportional to the angle of the linkage 3, and θ_3 is larger in the bent knee mode than in straight-leg mode, the input power increases when the bent angle increases.

In Fig.5, we can also find the influence of feedback gain on the walking motion. As the feedback gain increases from 7 Nm/rad to 8 Nm/rad, the step length increases only a little but the period increases notably while the bent knee angle is larger than 5 degrees. Therefore, it is not applicable to increase the velocity by increasing the feedback gain only. But in order to make the biped locomotion enter the limit cycle, we have to increase the feedback gain as the bent knee angle increases. For the straight-leg mode, k=4.6Nm/rad is enough to obtain a stable walk. But when the bent knee angle increases to 12 degrees, k=7Nm/rad is indispensable. From our preceding research, we know the clearance is influenced by the feedback gain k. The clearance reaches minimum in the middle of the swing phase. As k increases, the minimum clearance also increases. In the bent-knee walking model, the clearance decreases as the bent angle increases. Since the minimum clearance can be regarded as a margin of stable walking, it is necessary to increase the value of k in order to realize a steady walking.

Because the self-excited walking is a kind of natural motion of the mechanical system, the parameters of the mechanism have a great influence on the motion. First the range in which the mechanism can enter the limit circle is investigated for a model with the bent knee angle of 15 degrees. In fig.6, we examine the relationship between the velocity and the mass ratio and length ratio for various feedback gains k. In fig.6 (a), it is assumed that the total leg mass is $4kg$ and both the length of the shank and the thigh are $0.4m$. When the shank mass is around 30% of the total mass, the range of walkable k becomes the broadest. This means that it is easy to enter the limit circle at this mass ratio. This is just like our human, whose mass of thigh is about 2 times of the shank. But the speed reaches the maximum when the shank mass is a little more than the thigh mass. In fig.6 (b), it is assumed that the total leg length is $0.8m$ and both the mass of the shank and the thigh are $2kg$. We find that when the shank is a little shorter than the thigh, the speed reaches the highest. But the range of walkable k is broader when the shank length ratio is around 67%. From fig.6, we also note that as k increases, the velocity decreases instead of increase. This is because the increase in k does not help to increase the step length but only help to raise the foot. It is thought that the step length can be increased with the increase in k if the support leg can kick the ground at the same time.

In fig.7, we have also examined the effect of the mass ratio and length ratio on other walking characteristics in bent knee walking mode. Here the value of feedback gain and the bent knee angle are set to be 8Nm/rad and 15 degrees, respectively, in accordance with Fig.6. From Fig.7, we note that the step length, period, input power and specific cost increase as shank mass increases, but decrease as shank length increases.

In order to further speed up the walking, a circular curve foot is rigidly attached to the distal link. Here the mass of foot is ignored. In Fig.8, we can find that as the foot radius increases, the step length and velocity increase almost linearly because the supporting point of the stance leg is carried by the rolling motion of the cylindrical foot surface in addition to the angular motion as an inverted pendulum. As the radius of the foot reaches 0.4 m, the velocity is raised to 0.7 m/s. This means a 40% increase in contrast to the model without the foot. But we may encounter the problem of losing stability because the clearance will decline as the radius of foot increases. When the radius is larger than 0.4 m, the toe of the swing foot may strike the ground during the stride.

4. Conclusion

By giving the support leg a bent knee angle of no more than 17 degrees, the walking speed of the biped mechanism increases significantly as the knee angle increases. Meanwhile, the efficiency still remains higher in contrast to other biped machine. We also demonstrate the results of a faster walking by

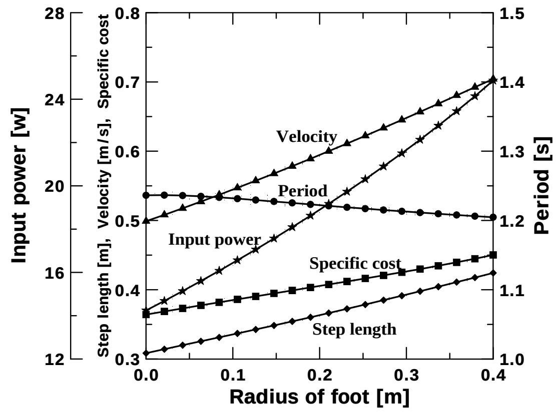


Fig.8 Effect of foot radius on walking characteristics ($\alpha = 10°$ and $k = 8.0 Nm/rad$)

increasing the mass of the shank, decreasing the length of the shank and increasing the radius of the foot, etc.. We also find that the period of the swing leg is primarily determined by the parameters of links and does not change so much. Therefore it is not easy to increase the velocity further by increasing the feedback gain k unless the support leg is driven forward by an ankle torque or by the kicking motion of foot.

We will continue the study on self-excited walking by introducing kicking motion of the support leg in order to increase the walking speed. To realize a biped running based on the self-excited or natural motion is our goal of the study.

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Appendix1

$$M1_{11} = I_1 + m_1 a_1^2 + m_2 l_1^2 + m_3 l_1^2$$
$$M1_{12} = (m_2 a_2 + m_3 l_2) l_1 \cos(\theta_2 - \theta_1)$$
$$M1_{13} = m_3 a_3 l_1 \cos(\theta_3 - \theta_1)$$
$$M1_{22} = I_2 + m_2 a_2^2 + m_3 l_2^2$$
$$M1_{23} = m_3 a_3 l_2 \cos(\theta_3 - \theta_2)$$
$$M1_{33} = I_3 + m_3 a_3^2$$
$$C1_{12} = -(m_2 a_2 + m_3 l_2) l_1 \sin(\theta_2 - \theta_1)$$
$$C1_{13} = -m_3 a_3 l_1 \sin(\theta_3 - \theta_1)$$
$$C1_{23} = -m_3 a_3 l_2 \sin(\theta_3 - \theta_2)$$
$$K1_1 = (m_1 a_1 + m_2 l_1 + m_3 l_1) g \sin(\theta_1 + \beta_1)$$
$$K1_2 = (m_2 a_2 + m_3 l_2) g \sin\theta_2$$
$$K1_3 = m_3 a_3 g \sin\theta_3$$

Appendix2

$$f_1(\theta_1, \dot{\theta}_1^-) = I_1 \dot{\theta}_1^- + \{a_1 m_1 v_{1x} + l_1(m_2 v_{2x} + m_3 v_{3x})\} \cos\theta_1 + \{a_1 m_1 v_{1y} + l_1(m_2 v_{2y} + m_3 v_{3y})\} \sin\theta_1$$

$$f_2(\theta_2, \dot{\theta}_2^-) = I_2 \dot{\theta}_2^- + (a_2 m_2 v_{2x} + l_2 m_3 v_{3x}) \cos\theta_2 + (a_2 m_2 v_{2y} + l_2 m_3 v_{3y}) \sin\theta_2$$

$$f_3(\theta_3, \dot{\theta}_3^-) = I_3 \dot{\theta}_3^- + a_3 m_3 v_{3x} \cos\theta_3 + a_3 m_3 v_{3y} \sin\theta_3$$

Appendix3

$$M2_{11} = I_1 + m_1 a_1^2 + m_2 l_1^2$$
$$M2_{12} = m_2 a_2 l_1 \cos(\theta_2 - \theta_1)$$
$$M2_{22} = I_2 + m_2 a_2^2$$
$$C2_{12} = -m_2 a_2 l_1 \sin(\theta_2 - \theta_1)$$
$$K2_1 = (m_1 a_1 + m_2 l_1) g \sin\theta_1$$
$$K2_2 = m_2 a_2 g \sin\theta_2$$