Foot Angle Determination for Efficient Heel-Toe Walking

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***Abstract*—Heel-toe walking can increase the stride length within the same joint limit of the robot. This paper proposes a method to compute the foot angle for heel-toe walking. In heel-toe walking, the value of the foot angle influences the movement of the legs, so it is proposed to select the foot angle to minimize the movement of the legs. The changes in stride and movement of leg with or without the heel-toe walking using the proposed foot angle is analyzed. The proposed aproach is demonstrated through experiments.**

***Keywords*—Humanoid walking, Locomotion, Heel-toe walking.**

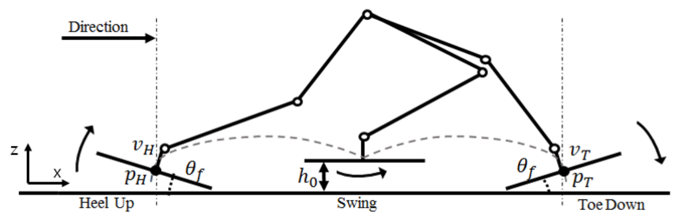

Fig. 1. Swing foot tractory consists of Heel up, Foot swing and Toe down.

1. Introduction

Humanoid robots are expected to be used for various applications. Fast and stable bipedal locomotions is one of the most important aspects in many applications. Humanoid robots can walk faster with longer strides, but joint limits of the leg limit the stride distance. Especially, in the case of flat walking in which the swing foot is parallel to the ground, the robot can not walk with a long stride because of the limitation of workspace. This limitation can be overcome by the heel-toe walking, which is like a person walking, taking off the ground from the heel to the toe in turn, moving in the direction of the robot, and then touching the ground in succession from the heel to the toe. Heel-toe walking can increase the stride length than flat walking, allowing the robot to walk faster, and can reduce the load of other leg joints[1]. Heel-toe walking also allows stair climbing, which was difficult with flat walking.[2].

In this paper, we propose an approach to select a certain foot angle between foot and ground during heel-toe walking. In the heel-toe walking with the same stride length, the foot angle is selected by analyzing the effect of the change in foot angle on the amount of motion of the leg. The foot angle and the foot trajectory for heel-toe walking were tested in V-REP simulator using DYROS JET robot.

2. Foot Angle for Heel-Toe walking

Heel-toe walking can reduce the range of joint motion, and the reduced range of motion can increase the stride length. Therefore, we propose to select the foot angle of heel-toe walking, which minimizes leg motion.

2.1. Heel-Toe swing foot trajectory generation

As shown in Fig. 1, one step of heel-toe walking is divided into three areas: heel up, swing, and toe down. Equation (1) shows the trajectory of the angle between the foot and the ground, taking into account the foot angle θ_f and the period of heel up T_{heel} and the period of toe down T_{toe}.

$$\begin{aligned} \theta_{heel}(t) &= \frac{\theta_f}{T_{heel}} t, \qquad && if \quad t \leq T_{heel} \\ \theta_{toe}(t) &= \frac{-\theta_f}{T_{toe}} (T - t), \qquad && if \quad t \geq T - T_{toe} \end{aligned} \tag{1}$$

where T is the period of one step of heel-toe walking. The foot trajectory at heel up, p_H is obtained using the foot step position p_f and the angle trajectory $\theta_{heel}(t)$ in Eq. (1).

$$p_{H,x}(t) = p_{f,x,i-1} + \frac{l}{2}(cos(\theta_{heel}(t)) - 1) \tag{2}$$

$$p_{H,z}(t) = p_{f,z,i-1} + \frac{l}{2} sin(\theta_{heel}(t)) \tag{3}$$

where $p_{f,i-1}$ is the position of the foot before the heel up, and l is the length of the foot. The trajectory of toe down $p_T(t)$ is obtained by substituting $p_{f,i-1}$ and $\theta_{heel}(t)$ in Eq. (2) and (3) with $p_{f,i}$ and $\theta_{toe}(t)$. The $p_{f,i}$ is the position of the foot after the toe down. The foot trajectory of the swing is generated using the cubic function so that the foot height at the midpoint is h_0 and the end of the heel up and the start of toe down are continuous.

2.2. Foot Angle for Little Movement of the Leg

As shown in Eq. (2) and (3), foot anlgle affects the swing foot trajectory, therefore the leg movement that depends on the swing foot trajectory is affected by the value of the foot angle. Therefore, for effective heel-toe walking, the foot angle is determined to minimize the movement of the legs. For predetermined stride length, the movement of the legs according to the foot angle was investigated empirically rather

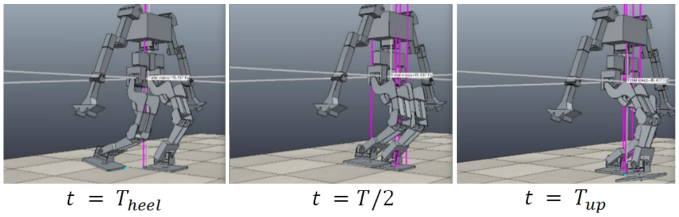

Fig. 2. Heel-toe walking simulation.

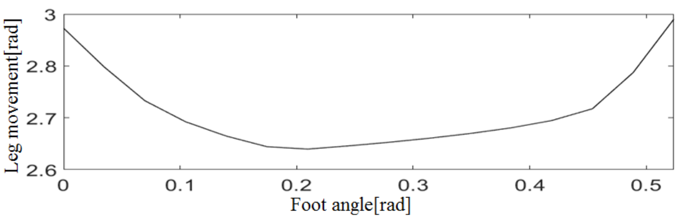

Fig. 3. Leg movements according to the foot angle when the stride length is 0.4m

than analytically. The leg movement used to obtain the foot angle is calculated as the sum of the leg joint changes for one step of heel-toe walking.

$$Legmovement = \sum_{i=1}^{N} \int_{0}^{T} |\dot{q}_i| dt \tag{4}$$

where N is the number of leg joint, T is the period of one step of heel-toe walking. This value is computed using the measured values at *1kHz* using Eq. (4), we compare different leg movements for each foot angle at a certain stride length, and select the foot angle that produces the smallest leg movement of that stride length.

3. Simulation and Discussion

The Dyros Jet used in the simulation has 32 degrees of freedom (DOF): 12-DOF for lower body, and 20-DOF for upper body. The Center of Mass trajectory is generated from the desired Zero Moment Point using Linear Inverted Pendulum Model [3]. V-rep simulator is used for testing the proposed approach.

3.1. Stride comparison between flat and heel-toe walking

The simulation of heel-toe walking is shown in the Fig. 2. With the hip height fixed at 0.8m, the maximum stride length is obtained by testing the movement of the legs by increasing the stride length, not exceeding the respective joint limits. The maximum stride lengths for flat and heel toe walking are 0.5m and 0.6m, respectively, and the simulation confirms that the maximum stride length of heel-toe walking is longer than that of flat walking.

3.2. Decreased leg movement in the heel-toe walking

The difference between the leg movements of flat walking and heel-toe walking was confirmed by simulation of one step with a hip height of 0.8m and a stride length of 0.4m. The foot

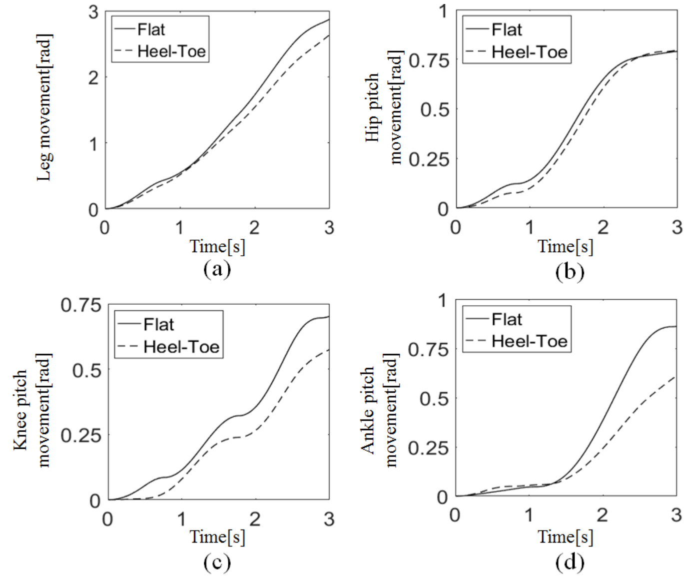

Fig. 4. Leg movement between flat walking and heel-toe walking of one step. The time of one step is 3 second, and the heel up and toe down are 0.4 second respectively. (a) Movements of leg joints, (b) Movements of hip pitch joint, (c) Movements of knee pitch joint, and (d) Movements of ankle pitch joint.

angle of heel-toe walking in the simulation was 0.2rad, which reduces the leg movement at 0.4m stride length, as shown in Fig. 3. Figure 4 shows the difference in leg movement for one step of flat walking and heel-toe walking. The movement of the whole leg joints, knee pitch joint, and ankle pitch joint shows 8%, 18% and 35% less heel-toe walking than flat walking, respectively.

4. Conclusion

This paper proposes a method to experimentally obtain a foot angle with less motion of legs during heel-toe walking. Simulation results show that the stride of the heel-toe walking is longer than that of the flat walking, and when the flat walking and heel-toe walking are performed with the same stride, the change of the leg joint is less in heel-toe walking. Future work will involve the implementation on the physical robot, and investigation about stability issue of the heel-toe walking.

Acknowledgement

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIP) (No. NRF-2015R1A2A1A10055798).

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