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GAIT ANALYSIS OF A LITTLE BIPED ROBOT

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Abstract. *Biped robots present higher mobility than four-wheeled robots that many researches have discussed the walking types and the standard of stability. From the aspect of general robot kinematics, this study tends to analyze the gait behavior of biped walking robots and further study each joint locomotion trajectory compared with cycloid spline and human walking. The purpose of this paper is to analyze gait behavior of a biped robot and motion trajectory of each foot joint. Trajectory planning method is required to achieve smooth walking through a cycloid spline interpolation. Finally, the Bioloid biped robot is programmed to walk smoothly and generate each joint locomotion trajectory compared with cycloid spline and human walking. The experimental results show that if robot control can be improved like human walking, i.e., the height variation in z-direction of hip joint trajectory approximating human walking, the waist or hip trajectories can be treated as a series of moving base frames.*
Keywords: Biped robot, Robot kinematics, Walking planning, Trajectory planning

1. **Introduction.** Biped robots present higher mobility than four-wheeled robots that many researches has discussed the walking types and the standard of stability [1-3].

A trajectory is the path followed by biped robots, plus the time profile along the path. Numerical solution is used to calculate the walking trajectory instantaneously [4]. The drawback is the duration of calculation time. Some researches observe humans walking types to generate walking trajectories [5]. Trajectory planning can be either in joint space (directly specifying the joint angles with time) or in Cartesian space (specifying the position and orientation).

Three kinds of path generation were commonly exploited to plan the motion trajectory of biped robots. They are exponential spline, cubic polynomial spline and cycloid spline. Exponential spline was no longer used. Huang et al. [6] developed desired trajectories by cubic polynomial spline interpolations, which was considered more complicated as the spline equations have to be recalculated for different action cycle periods, step heights, and step lengths. Hwang et al. [7] applied cycloid spline interpolations, which were similar to the human walking trajectory and the function values were easily revised. Wang et al. [8] improved the cycloid trajectory from its geometry.

From the aspect of general robot kinematics, this study tends to analyze the gait behavior of biped walking robots and further study each joint locomotion trajectory compared with cycloid spline and human walking.

2. **Walking Gait Cycles.** Biped robot walking can be treated as a periodic phenomenon. A complete walking gait cycle is divided into two major phases: double-leg stance phase and single-leg stance phase (Figure 1). The former refers to both soles standing on the ground, while the latter indicates one sole landing on the ground as the support leg and the other leg swinging in the air as the swing leg, then stepping to the next position as the support leg [5].

The sole cycloid trajectory equations in the gait cycle (Figure 2) can be derived as the following Equation (1) [7]:

$$\begin{aligned} X(t) &= \frac{D_2}{\pi}\left[2\pi\frac{t}{T} - \sin\left(2\pi\frac{t}{T}\right)\right] \\ Z(t) &= \frac{h}{2}\left[1 - \cos\left(2\pi\frac{t}{T}\right)\right] \end{aligned} \tag{1}$$

where D is the distance of one step, h is the height of one step (the pitch diameter of the cycloid), T is the period of a step, and t is the time parameter.

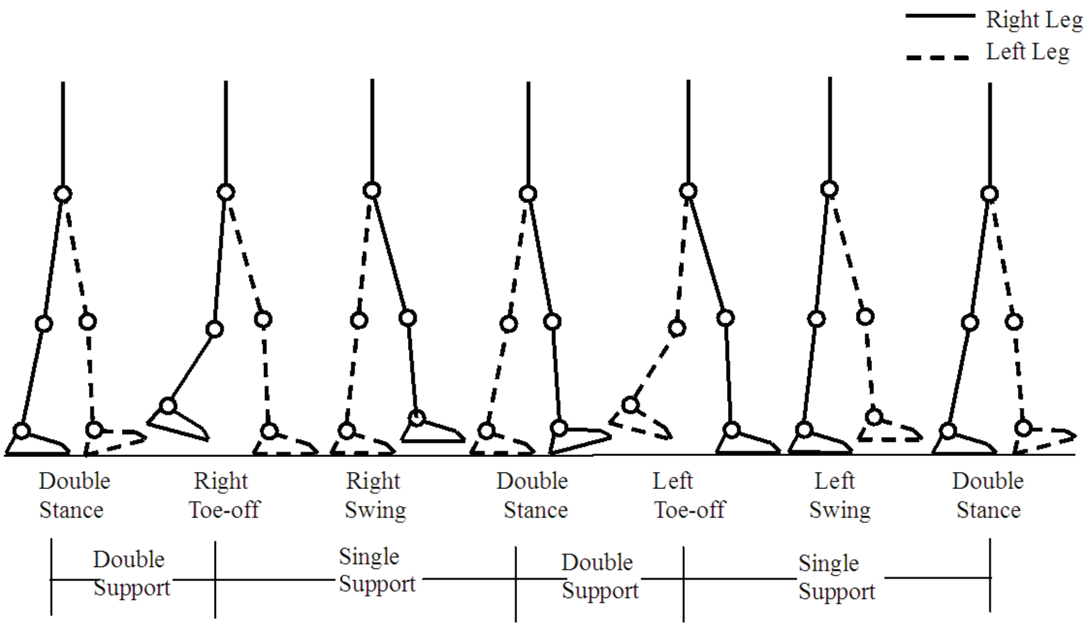

FIGURE 1. Human walking gait cycle

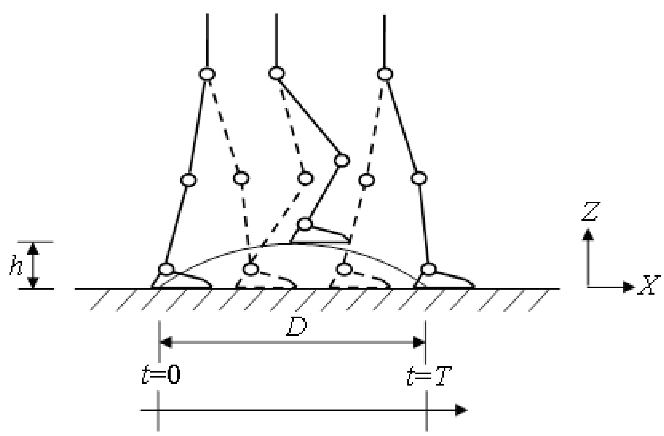

FIGURE 2. Cycloid walking motion

3. **Experiment.** Bioloid robot, designed by ROBOTIS, was programmed to walk smoothly and used to analyze the gait behavior in this study (Figure 3). The step length was set $D = 75$mm and the leg-lift height $h = 9$mm.

In the locomotion laboratory, reflecting markers mounted on robot joints are captured by charge-coupled device (CCD) cameras. Total 106 pictures were captured. Successive walking snapshots are taken in Figure 4. Three seconds after the Bioloid robot was set to the initial configuration to avoid robot unsteady state walking. The time between each snapshot is 0.03 second. The pictures measure each joint position during walking cycle, and the relations between the joint position and time duration.

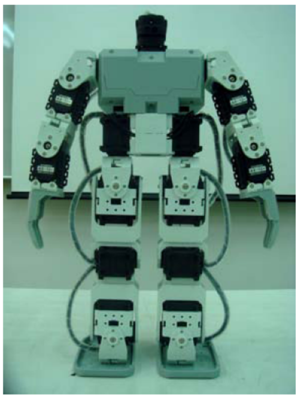

Figure 3. Front view of Bioloid robot

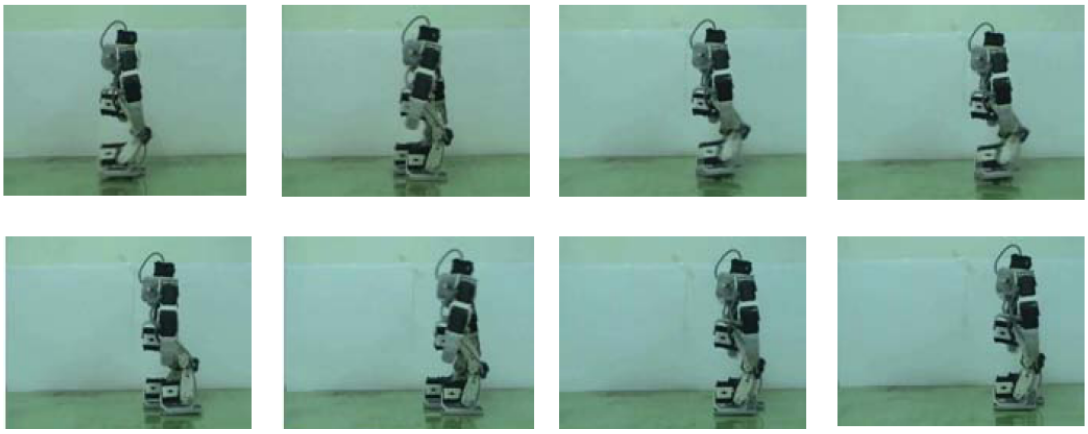

Figure 4. Walking snapshots of Bioloid robot

4. **Analysis.** Logic coverage criteria are mainly used for formal specification-based testing [3]. It generates test cases by analyzing the predicates and literal truth value relationship. The formal specification is constituted by a series of states and transitions. Long-term practice shows that the system boundary is most likely to make system wrong. Boundary state is a state that at least one of those state variables can be taken to the extreme value of its sub-domain state. Aim at the logic coverage criteria with little regard to the boundary, this paper proposes a series of logical boundary coverage criteria based on paper [1,2].

In Figure 5, the curve shows the relationship between travelling distance and time duration of the foot sole. The horizontal region shows the sole standing on the ground stable and flat, and the oblique line is the transition process between steps, where the slope showed the sole moving uniformly during swinging phase with maximum instantaneous speed approximately 317.7mm per second.

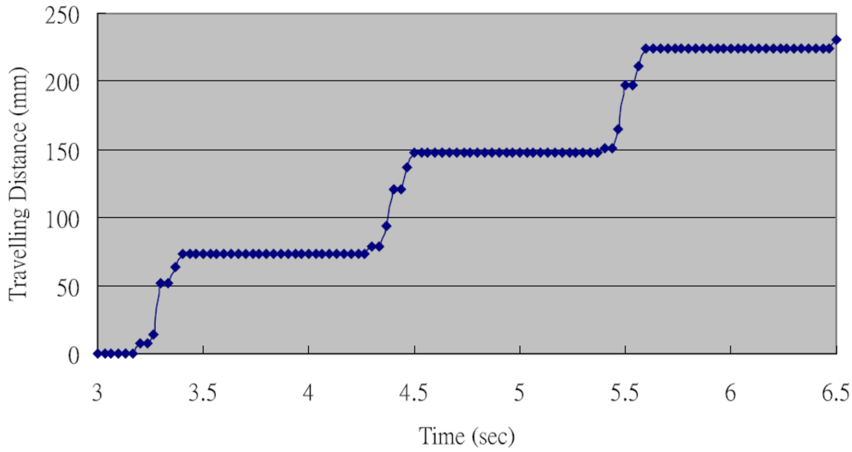

Figure 5. Relations between travelling distance and time

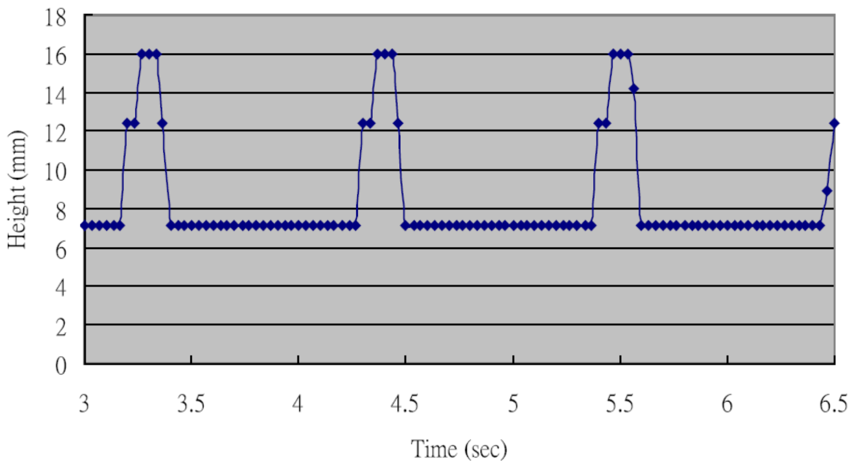

Figure 6. Relations between travelling height and time

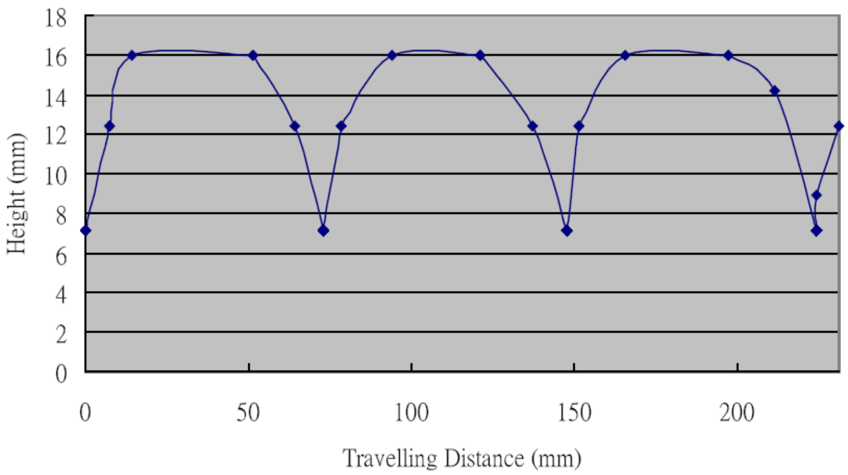

Figure 7. Relations between travelling distance and height

In Figure 6, the curve shows the relationship between travelling height and time duration of the foot sole. In Figure 7, the curve shows the relations between travelling distance and height. That is, it presented the side view of sole joint.

The duty factor, β, is the time ratio between support period and locomotion cycle. For example, $\beta = 0.7$ means that one leg is in stance phase 70% of the gait time period. With $\beta \geq 0.75$ the gait is called static [5]. In Figure 6, the horizontal line means that the sole

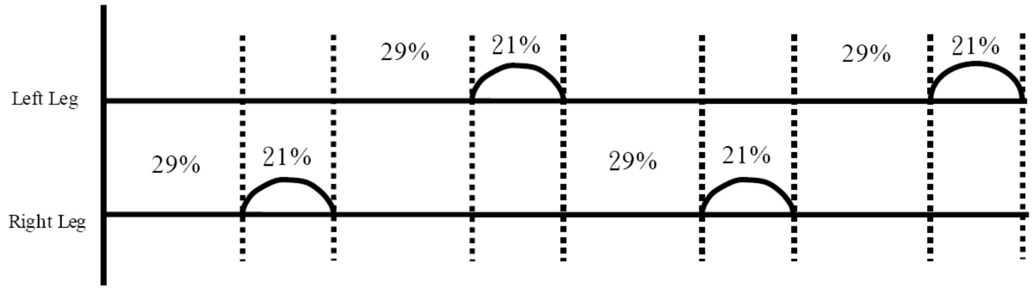

Figure 8. Biped walking cycle of Bioloid robots

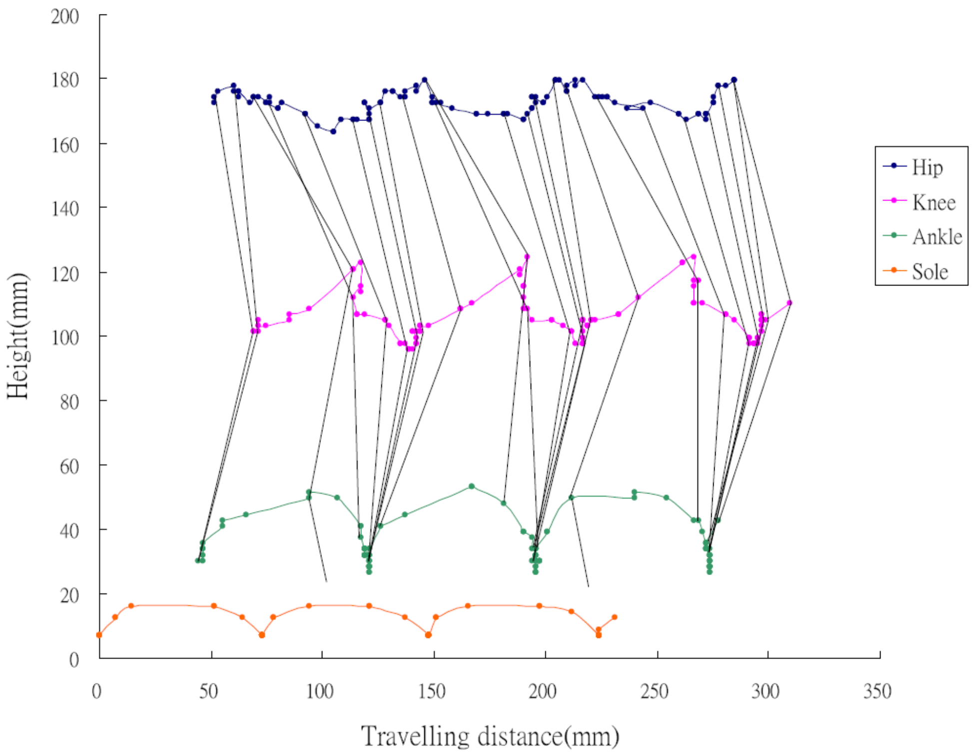

Figure 9. Result of Bioloid robot walking

contacts the ground and the duty factor $\beta = 0.79$, which presents the swing cycle of the leg was about 21% of the walking cycle period, as shown in Figure 8.

4.1. **Trajectories comparison of joint measurement with cycloid spline.** Figure 9 is a stick graph of Bioloid robot walking where the trajectories of hip, knee, ankle, and sole can be depicted. Figure 10 shows the comparison between Bioloid hip joint trajectory and the upward opening cycloid spline, where the parameters were the step length $D = 75$mm and the step height $h = 12.5$mm, and $T = 0.465$ second. As Bioloid robot walks forward, the knee joint would move first and the hip joint followed. The figure revealed that the hip joint trajectory was behind the cycloid.

Figure 11 displays the comparison between the knee joint measurement and the upward opening cycloid, where $D = 75$mm, the step height $h = 27$mm, and $T = 0.465$ second. The figure showed that the knee joint trajectory was ahead of the cycloid spline during the leg lifting off the ground to the highest point; the knee trajectory was behind the cycloid spline from the highest point dropped to the ground.

Figure 12 presents the comparison between the ankle joint measurement and the downward opening cycloid spline, where the parameters $D = 76$mm, $h = 25$mm, and $T = 0.465$

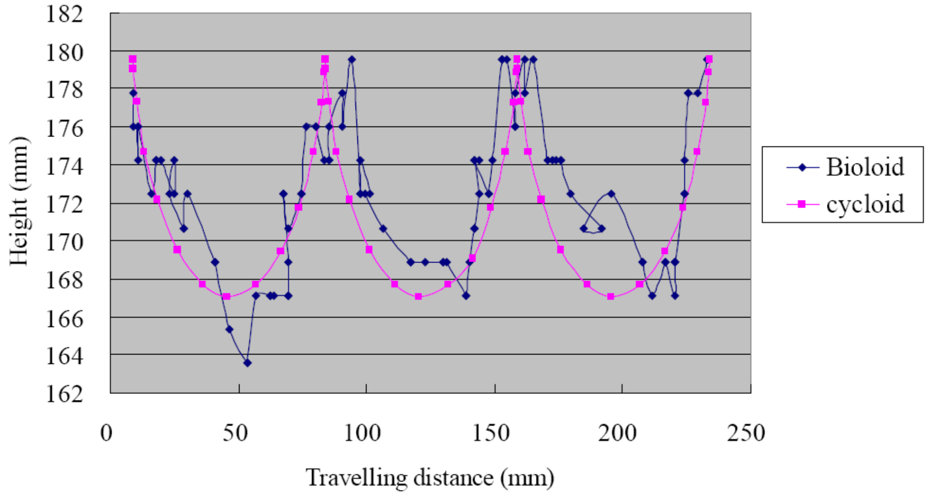

FIGURE 10. Hip trajectories comparison between Bioloid spline and cycloid spline

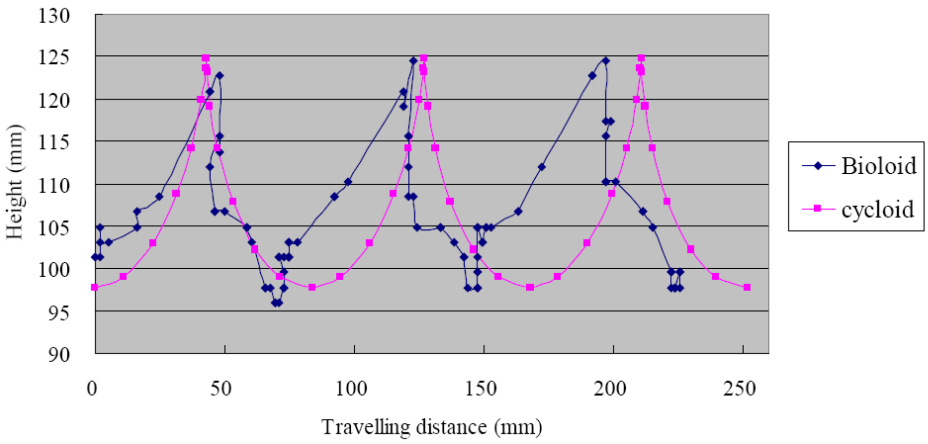

FIGURE 11. Knee trajectories comparison between Bioloid spline and cycloid spline

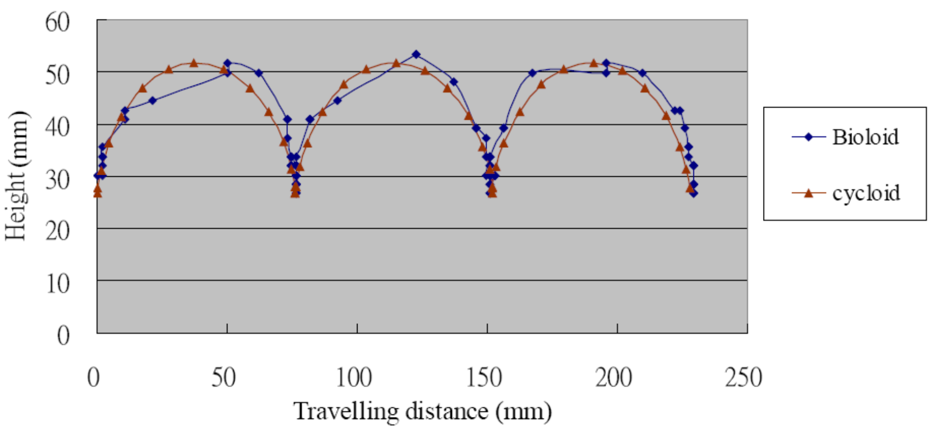

FIGURE 12. Ankle trajectories comparison between Bioloid spline and cycloid spline

second. The two splines were close in the figure. Figure 13 showed the comparison between the sole measurement and the downward opening cycloid, where the parameters $D = 75$mm, $h = 9$mm, and $T = 0.465$ second. The sole walking trajectory was even close to the cycloid spline in the figure.

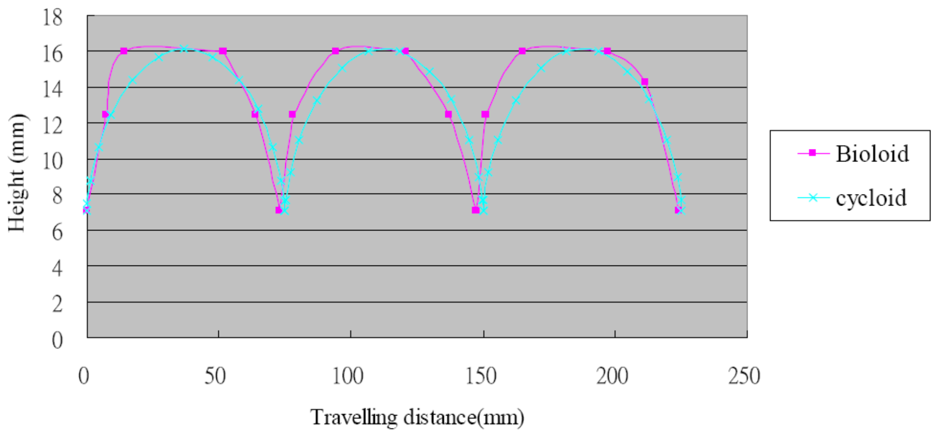

FIGURE 13. Sole trajectories comparison between Bioloid spline and cycloid spline

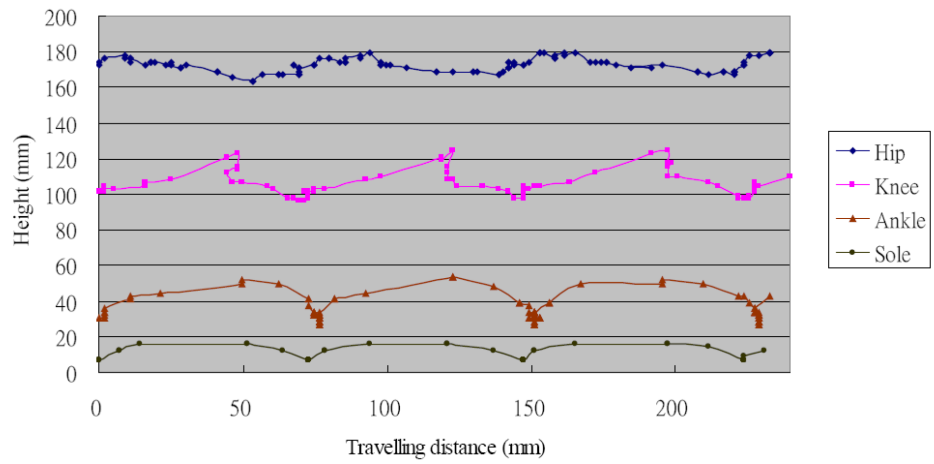

FIGURE 14. Walking trajectories of Bioloid robot

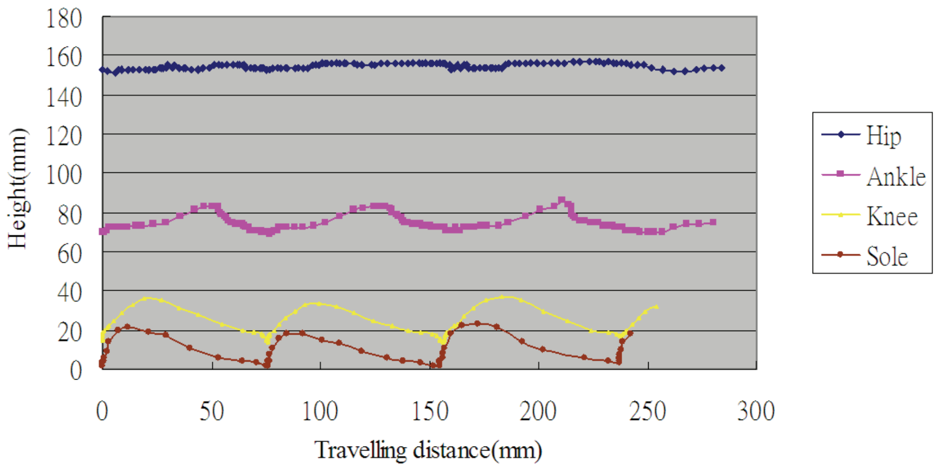

FIGURE 15. Trajectories of human walking

4.2. **Comparison of walking trajectory between Bioloid robots and humans.** Figure 14 displays the joint trajectories of Bioloid robots. The ankle and the sole were close to the ground so that the lowest points of two upward opening trajectories are coincident with the positions where foot contacts the ground. The height variation in z-direction of hip joint trajectory is 12.5mm. What is more, the knee joint swung up and down that the trajectory was ahead of the cycloid spline during the period which begins with the foot striking the ground till the highest point.

Figure 15 shows the trajectory of a 175cm high human walking, which is approximately 5 times height of Bioloid robot, with step distance 570mm, step height 157.5mm, and the average speed 233.3mm per second. In comparison with Figure 14, the height variation in z-direction of hip trajectory is 4mm, which is only 32% of Bioloid robot. It appears that human walking is much more stable and smooth than the robot. Both knee trajectories are downward opening spline. The trajectories of the ankle joint and the sole are quite similar. However, the highest points of both ankle and sole trajectories for humans appear in the front portion of trajectories, while the highest points of both ankle and sole trajectories for Bioloid robot appear near the middle of trajectories.

5. **Conclusions.** In this paper, the kinematic structure and the coordinate frames of a Bioloid robot are constructed to analyze biped robot locomotion. Whether the gait of biped robots walking is static or dynamic, the movement of the center of mass or zero-moment point should be considered. The walking trajectories of ankle and sole of the robot were close to the cycloid spline while both trajectories of hip and knee were not the same. Therefore, once the inverse kinematics solutions of the six joints of each foot can be solved, the coordinate systems of the sole cycloid spline trajectory can be treated as a series of moving base frames to obtain joint parameters for planned hip positions. On the other hand, if robot control can be improved like human walking, i.e., the height variation in z-direction of hip joint trajectory approximating human walking, the waist or hip trajectories can be treated as a series of moving base frames.

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