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3D Quasi-passive Walking of Biped Robot with Flat Feet - Gait Comparison between Passive Walking and Quasi-passive Walking -

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Abstract. Currently, many bipedal robots have been proposed to realize the high energy efficiency walking. The control input isn't required for the passive dynamic walking. Generally, a foot of passive dynamic walking robot is an arc foot. In this paper, it is intended to establish a control method and control mechanism to achieve the energy efficient and the stable gait. Therefore, we developed 3D quasi-passive walker with flat feet driven by an antagonistic pneumatic artificial muscle. An antagonistic mechanism is constituted by a pair of McKibben muscle. And, an antagonistic pneumatic system is used as joint actuators of linkage mechanisms which control the torque, joint stiffness and position simultaneously. This paper shows that the 3D quasi-passive walking in the level ground can realize by the swinging (simple) input of the frontal direction, and the stride of the robot is proportional to lateral-plane input. Finally, the gait of the bipedal robot is analyzed by COP (Center of Pressure) and ROS (Roll-Over Shapes).

Keywords: *Bipedal Robot; Flat Feet; 3D Quasi-passive Walking; Center of Pressure; Roll-Over Shapes*

I. Introduction

An energy efficiency and locomotion such as human [1] are very important issues in a bipedal robot walking. Recently, a passive dynamic walking has received considerable research attention. The investigation of passive dynamic mechanism can help to solve both issues. The idea of passive dynamic walking was pioneered by T. McGeer [2]-[4] who studied the so-called compass gait biped, a two DOF (Degree Of Freedom) walker that can achieve the passive dynamic walking down shallow inclines powered only by gravity. Most previous studies of passive dynamic walker with arc-shaped feet (no feet) have been constrained by the locomotion of the sagittal plane [5][6]. Since the ground-direction contact occurs only at a point, the arc-shaped feet provide insufficient friction against the ground. Passive walkers with arc-shaped feet are unstable in the upright state.

M. Wisse et al.[7]-[9] studied a 2D passive walker with flat feet and ankle springs by utilizing the equivalence between the torsional spring and the arc-shaped feet. Therefore, the arc-shaped feet can be replaced by flat feet that are mounted on ankles with torsional spring stiffness.

In this paper, we develop the 3D quasi-passive walker with flat feet which are driven by antagonistic pneumatic mechanisms. A typical antagonistic pneumatic mechanism consists of a pair of McKibben artificial muscles. An antagonistic pneumatic mechanism have a low joint stiffness when unactuated, leaving the joints to behave almost passively at zero pressure. At higher pressures, antagonistic pneumatic mechanisms behave as progressively stiffer springs. We experiment the bipedal robot with artificial muscles such as springs on the slope, and perform an experiment of 3D quasi-passive walking in the level ground using artificial muscles as actuator.

The remainder of the paper is organized as follows. Chapter 2 summarizes the principle of 3D quasi-passive walking, and antagonism pneumatic artificial muscle. Chapter 3 then presents the structure of quasi-passive dynamic walker. Chapter 4 describes a method of our walking experiment conducted on a slope and a level ground, and each results. Chapter 5 presents a method for gait analysis; it performed using COP (Center of Pressure) and ROS (Roll Over Shapes).

Finally, the paper concludes with the results of the 3D quasi-passive walking in the level ground.

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II. Relations of Arc foot and Equivalent spring constant

Wisse et al. showed that the rigid arc-shaped feet can be replaced by flat feet that are mounted on ankles with the stiffness of torsional spring. The spring stiffness has a similar effect as the foot radius; it reduces the sensitivity to disturbances due to friction (slipping) and collisions, and thus improves the disturbance handling. Therefore, 3D passive dynamic walking with flat feet are walking forms that extend the lateral motion to 2D passive dynamic walking in sagittal plane as indicated in Fig. 1. They studied a 2D passive walker with flat feet and ankle springs by utilizing the equivalence between the torsional spring and the arc-shaped feet.

A typical antagonistic pneumatic mechanism consists of a pair of McKibben artificial muscles [10] as shown in Fig. 2. The developed walker [11] has the equivalent characteristic of torsional spring to the walking robot by equipping antagonism pneumatic artificial muscle. It is confirmed that sustainable 3D quasi-passive walker can walk on a slope. In this study, we measure the natural frequency, the ankle rigidity and the stride of the walking robot based on 3D quasi-passive gait on the slope.

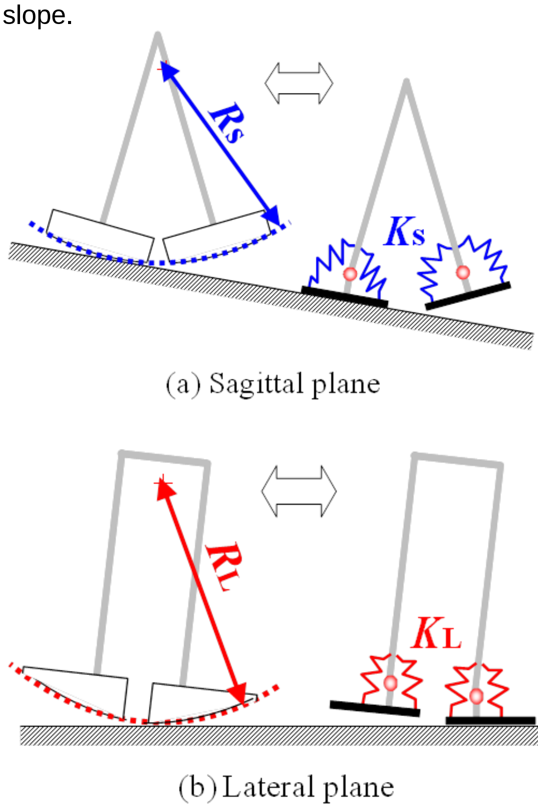


Figure 1. 3D passive dynamic walking with flat feet.

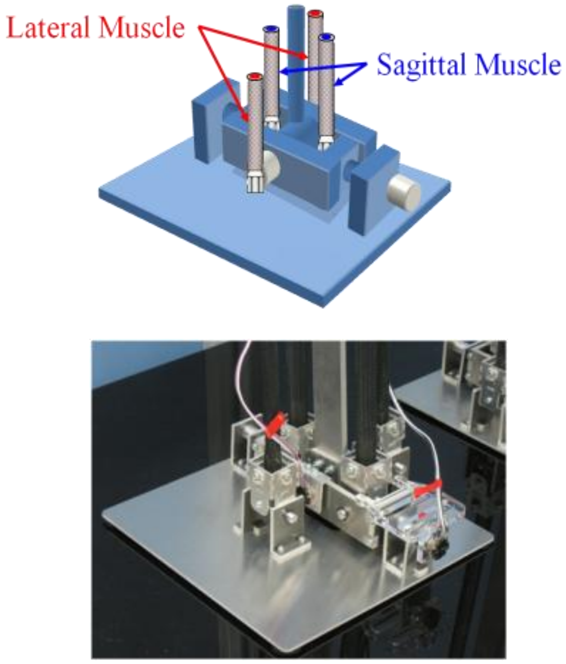


Figure 2. Structure of ankle joint.

III. Structure of Bipedal Robot

Fig. 3 and Fig. 4 showed whole structure and dimensions of the quasi-passive dynamic walker ("TENBU" Prototype 3). TENBU produced in this study has two legs. The prototype robot doesn't have knees and their ankles have 2 DOF in roll and pitch motions. The walker consists of a hip, two straight legs and two flat feet. The ankle joint has two DOF about roll and pitch axes and connecting shaft has single DOF. There are five internal DOF. The artificial muscles are attached between the leg and the ankle. They are fitted to sagittal and lateral plane by two each. Therefore, we can control only the ankle motion.

The bipedal walking robot is equipped with micro-computer (Renesas Co. Ltd., H8/3664), battery, air tank , On/Off valves and wireless module(ZigBee). Passive dynamic walking is a gait path that depends on the dynamic characteristics of biped walking robot. It is desirable that there is no external cable(umbilical cable) as much as possible. Thus, "TENBU" robot is a self-contained robot. The trial number of the walking experiment in level ground is about 5 times by using two air tanks(air capacity : 4 liter). To increase friction on the ground, the circular rubber sheet with the force sensor is attached to the soles of the feet.

Fig. 5 shows the control circuit to operate the robot. The micro-computer adjusts the internal pressure of artificial muscle by controlling the On/Off valve. The embedded controller that is the micro-computer gets the output voltage from six potentiometers and eight force sensors. Then, the sampling period of the On/Off valve control was about 30 ms. However, the period of the sampling data is 70 ms by using the wireless ZigBee module(57600 bps).

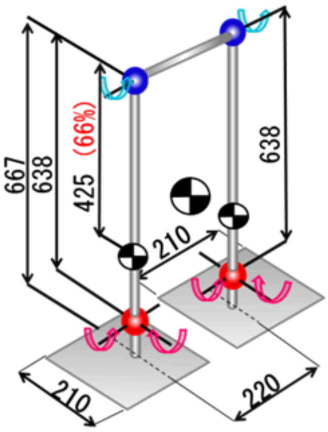


Figure 3. Structure and size of quasi-passive dynamic walker.

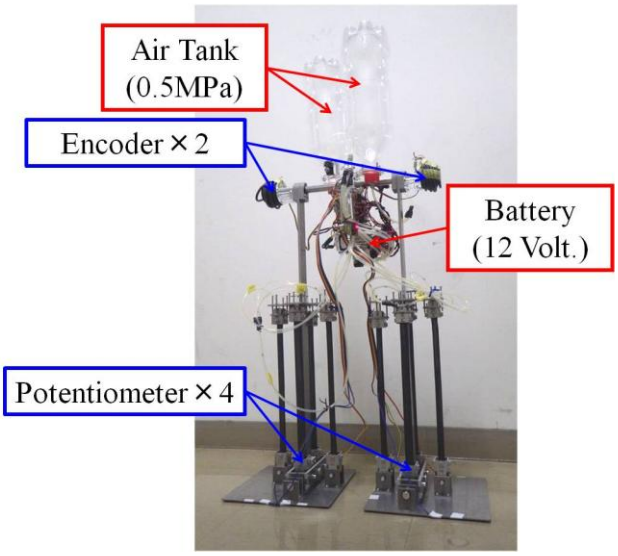


Figure 4. Quasi-passive dynamic walker (TENBU 3).

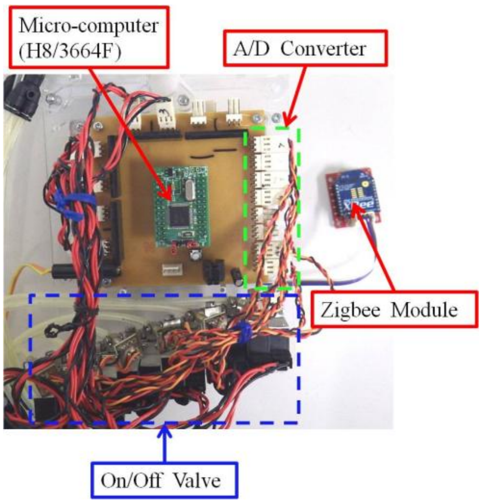


Figure 5. Control circuit

IV. The experiment of 3D quasi-passive walking

In this chapter, we carried out the experiment of 3D quasi-passive walking on the slope to confirm the effectiveness of the produced ankle experimentally and to acquire basic walking experiment in the level ground by lateral-plane input based on the walking data.

A. Quasi-passive walking on the slope

In this paragraph, we state the 3D quasi-passive walking experiment on the slope. Fig. 6 shows the most common experimental result in which the 3D quasi-passive walker walked on the slope.

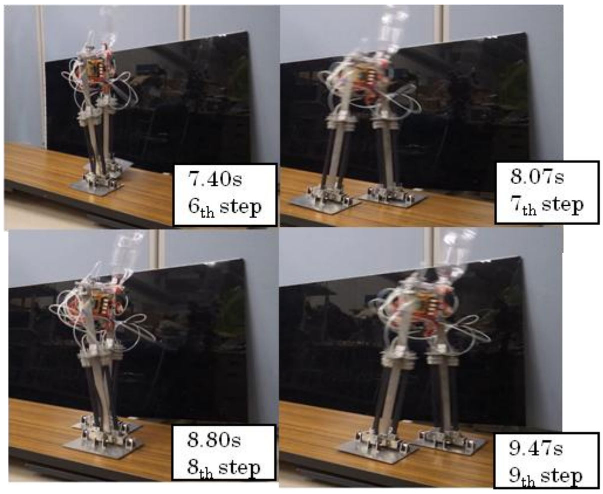


Figure 6. 3D quasi-passive walking on the slope.

The experimental conditions of the passive walking are as follows.

1. Angle of inclination of the slope : 4.0[deg.]
2. Internal pressure of artificial muscles :

Sagittal plane direction : 0.20[MPa]
Lateral plane direction : 0.15[MPa]

where the valve controller is only operating to keep the internal pressure of the McKibben artificial muscles to a constant value to maintain ankle rigidity constantly.

As results of 3D quasi-passive walking experiment, the following gait data were obtained. The sustained walking are possible under this conditions:

1. Average step : 149[mm]
2. Average walking period : 1.36[s]
(Half period : 0.68[s])
3. Average walking speed : 220[mm/s]

B. The experiment of 3D quasi-passive walking in the level ground

One of the research purposes includes that the bipedal robot realize 3D quasi-passive walking in the level ground. Therefore, we examined the level ground walk by swing motion input (Lateral plane direction) using the quasi-passive walking without the knee as the first step in this paper.

We let fluctuate internal pressure P_R and P_L of the antagonism pneumatic artificial muscle attached to lateral plane direction of each ankle joint as following equation.

$$P_R = P_{AMP}\sin(\omega t) + P_O \quad \text{:[MPa](Right)} \qquad (1)$$

$$P_L = P_{AMP}\sin(\omega t - \pi) + P_O \quad \text{:[MPa](Left)} \qquad (2)$$

where P_{AMP} is amplitude, ω is angular frequency and P_0 is initial pressure. The initial pressure set up the sagittal plane muscle 0.20 MPa and lateral plane muscle 0.15 MPa from the experimental results of the passive walking on the slope. The angular frequency ω is set approximately 1.36s (Half period : 0.68s) like the walking period of the 3D quasi-passive walking on the slope. In addition, TENBU is inclined approximately 4 degrees forward like being on the slope. The internal pressure of sagittal plane muscles is constantly, and lateral plane pressure is controlled by swing motion input (Eqs. 1 and 2) during the walking experiment in the level ground.

Fig. 7 shows the most common experimental results in which 3D quasi-passive walking in the level ground. TENBU was able to realize 3D quasi-passive walking in the level ground though it was only gave very simple lateral-plane input.

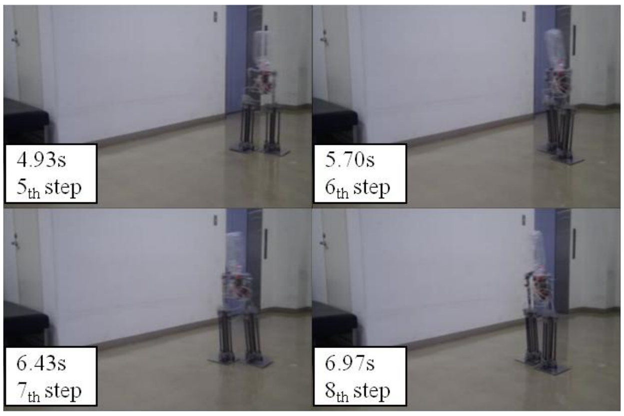


Figure 7. 3D quasi-passive dynamic walking (Level-ground).

V. Gait Analysis and Discussion

The gaits (COP and ROS) between the passive dynamic walking on the slope and the quasi-passive walking in the level ground are compared in this Chapter.

A. COP(Center Of Pressure) path

Circular rubber sheet with the force sensor is attached to the soles of the feet to increase friction in the ground. Fig. 8 shows the setting position of the force-sensors and coordinate system. We analyze the 3D quasi-passive dynamic gait i.e., COP by means of the physical information that are obtained by the four force-sensors. COP is the path which calculated the gravity center of the walking TENBU's sole using force-sensors.

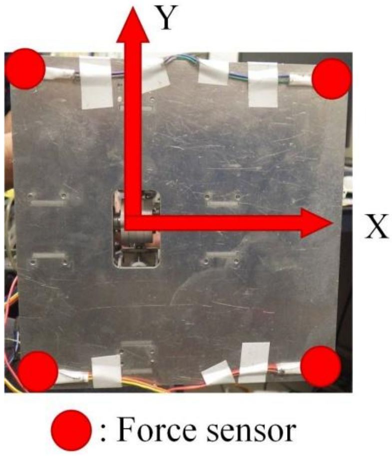


Figure 8. Force-sensor of sole

As a sample of experimental results, the lateral and anterior-posterior displacement of the instantaneous COP (Blue line) during stance phase in the bottom of the right foot has been shown in Fig. 9 and Fig. 10. This observational data recorded the COP displacement in robot walking. In this research, the COP path from force sensor's data (red-circle position) was investigated.

Fig. 9 shows the COP path of the passive dynamic gait. After COP path shift to the outside of lateral plane from center part of heel, COP moves to the center part of tiptoe in case of 3D quasi-passive walker. From Fig. 9, the COP behavior of the passive dynamic gait is almost the same trend of human COP. However, in the region (Green circle) of the tiptoe, there is difference in the COP behavior between humans and robot. This behavior cause is due to a small stride length 210 mm (about 204 mm Heel-toe length).

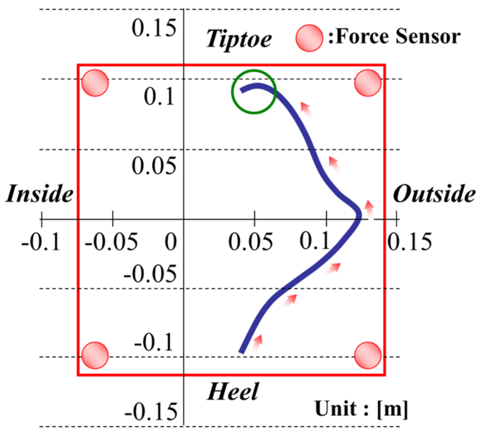


Figure 9. COP path (Passive dynamic walking)

Fig. 10 shows the COP path of the quasi-passive dynamic gait. After COP path shift to the outside of lateral plane from middle part of heel, COP moves to the middle part of tiptoe in case of 3D quasi-passive walker. Fig. 9 and Fig. 10 show that the COP behavior of the quasi-passive dynamic gait is different from the behavior of the passive dynamic walking. The stride of the quasi-passive dynamic walking has smaller than the passive dynamic walking.

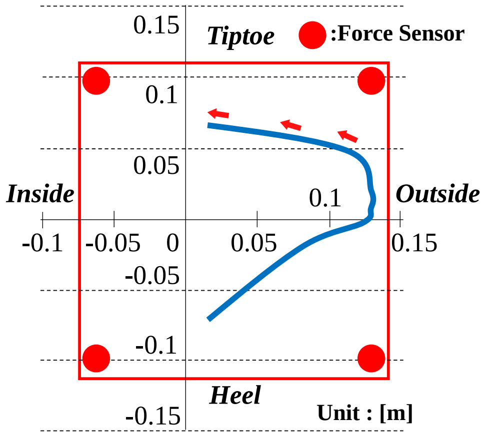


Figure 10. COP path (Quasi-passive dynamic walking)

B. *ROS (Roll-Over Shapes) Path*

In previous section, we obtained the COP path of each foot, using force sensors. We also measured the joint angles of the hip and ankle of each leg. In this section, we describe the ROS calculated from COP.

The ROS is the trace which expressed the COP at the ankle-knee coordinate system of the support leg, and can be summarized "the location of the pressure during the walking". Fig. 11 shows an example of the COP and the ROS. Fig.10 plotted the knee, the ankle, the COP every period of time. When the ankle-knee coordinate system is constructed by each point of knee, ankle and COP, the downward arc-shaped curve is the ROS. In case of ankle-knee coordinate system, the ankle joint is considered to be the origin , and the knee direction is regarded as one of the coordinate axes.

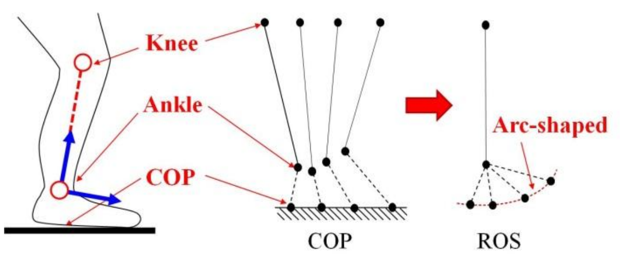


Figure 11. ROS(Roll-Over Shapes)

We calculated the ROS[12] of the foot with desired stiffness and approximated arc-shape. As an example, the measurement data (Red-circle point) and the approximated ROS (Blue line) are shown in Fig. 12 and Fig. 13.

Fig. 12 shows that an approximated radius 0.252 m of the sagittal ROS is substantially equal to the desired radius 0.245 m that was determined by the proposed method[11]. Then, the approximated radius 0.432 m of the lateral ROS also is substantially equal to the desired radius 0.458 m. In summary, it was demonstrated that rollover shapes of the sagittal and lateral plane can be adjusted by the internal pressure of the antagonistic pneumatic mechanism.

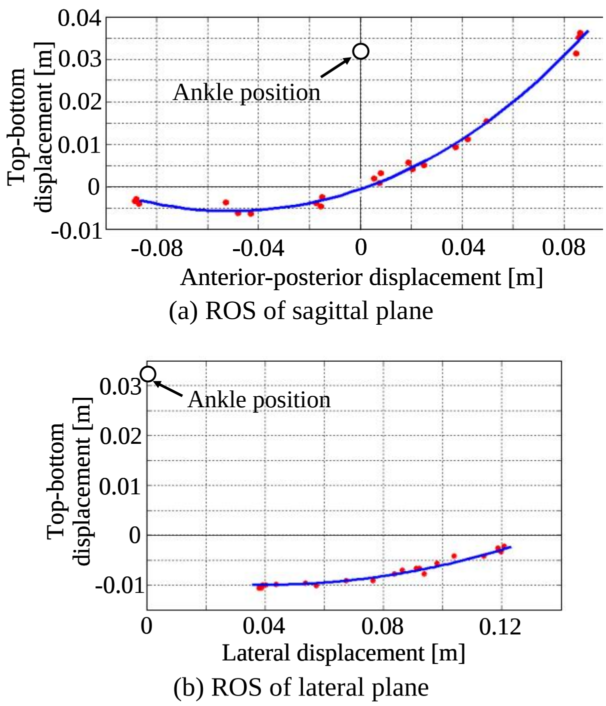
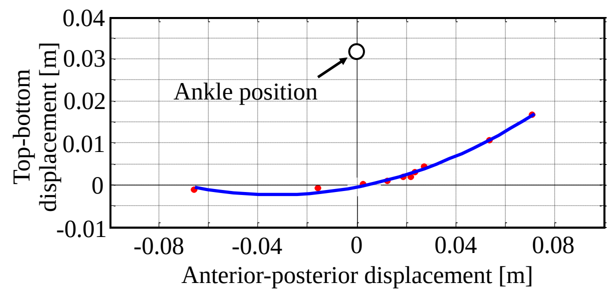
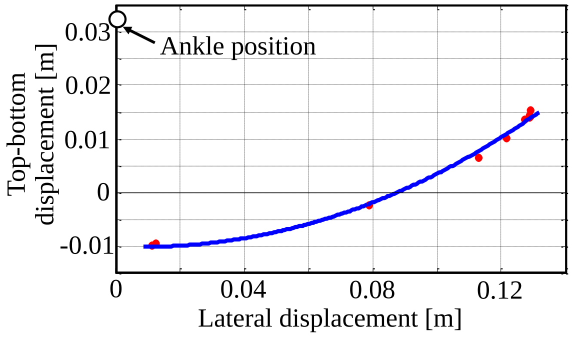


Figure 12. ROS path (Passive dynamic walking)

Fig. 13 shows that an approximated radius of the sagittal ROS is 0.296 m. Then, the approximated radius of the lateral ROS is 0.316 m. In particular, the obtained radius of the lateral ROS is not equal to the desired radius 0.458 m. When ROS path moves outside of a foot, the biped robot turns over. In other words, the static stability margin is small.



(a) ROS of sagittal plane



(b) ROS of lateral plane

Figure 13. ROS path (Quasi-passive dynamic walking)

C. Discussions of walking speed and stride

The obtained step period is 0.67s, which is almost same as the designed natural frequency 4.73rad/s (half cycle:0.66s). Thus, the stiffness of the joint is adjusted suitably by controlling the pressure of artificial muscle. We realized the 3D quasi-passive walking for the biped robot with flat feet driven by an antagonistic pneumatic artificial muscle. However, the non-dimensional walking speed; (walking speed)/ $\sqrt{g \cdot l_s}$ is about 0.12, which is two times smaller than the walking speed 0.3 of human. Although the natural frequencies of the sagittal plane and the lateral plane are synchronized, the slow walking speed (small stride) is caused by the small amplitude of the lateral plane.

Fig. 14 shows the relations between the stride and every half period. Half period that TENBU can walk from 0.3s to 0.5s. In addition, we obtained the following equation that approximates to the liner function by the least-squares method from Fig. 11.

$$b = 320T_p - 70.4 \qquad \text{[mm]} \qquad (3)$$

where b is stride, T_P [s] is half period. Therefore, it is thought that the stride and the period of lateral-plane inputs is proportion.

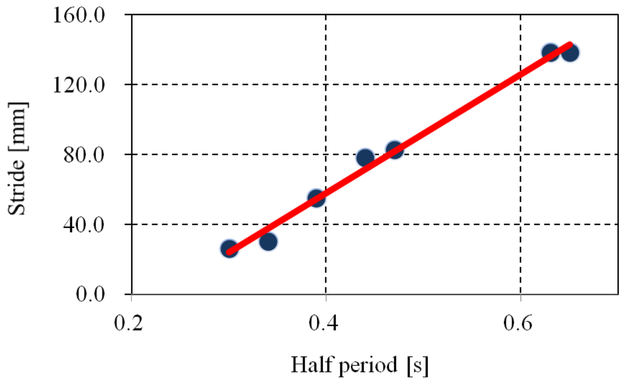


Figure 14. Relation between stride and half period.

VI. CONCLUSIONS AND FUTURE WORKS

This paper designed and produced the bipedal robot which had the antagonism pneumatic artificial muscle with flat feet. And we carried out 3D quasi-passive walking experiment. In addition, we carried out 3D quasi-passive walking experiment in the level ground by simple swing motion input to the lateral direction. And, we analyzed the 3D quasi-passive dynamic gait such as COP and ROS by means of the force sensor. The COP behavior of robot gait was almost the same trend of human COP.

As a result, we were able to get the resulting knowledge.

1. The quasi-passive dynamic walker was able to be realized 3D quasi-passive walking in the level ground by means of giving simple swing motion input to the lateral direction.
2. The ROS of the sagittal and lateral plane could be adjusted by the internal pressure of the antagonistic pneumatic mechanism in the case of the passive dynamic walking.
3. The ROS behavior of lateral plane became almost the same ROS of sagittal plane by giving simple swing motion input.
4. The proportional relation between the half period of swing motion to the lateral direction and the walking stride was discovered.

In general, the passive dynamic walking has a problem such as the small range of initial conditions. But, since the feasible region of entrainment phenomenon is relatively large, the initial conditions of the robotic walking are not difficult for the prototype robot of 3D passive dynamic walker. We will examine the robustness of entrainment phenomenon as a problem to be solved in the future. In future works, we have to increase the amplitude of the lateral plane in order to increase the walking speed. And we hope to develop the 3D quasi-passive walker with a knee in the level ground.

VII. References

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