The Effect of Foot Structure on Locomotion of a Small Biped Robot

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Abstract. This paper is a presentation of a work that consists of considering a novel foot structure for biped robot inspired by human foot. The specific objective is to develop a foot mechanism with human-like toes for a small biped robot. The chosen architecture to present the biped includes ten degrees of freedom (DoF) on ten articulations between eleven links. Our study considers the effect of varying foot structure on a walking process of the robot in simulation by ADAMS (MSC software, USA) through gait generation method. In toe mechanism, aiming to reduce the energy consumption, the passive joint was selected as the toe joint. The center of gravity (CoG) point trajectories of the robot with varying toe is compared with each other in normal motion on flat terrain to determine the most consistent toe mechanism. The result shows that the selected foot structure enables the robot to walk stably and naturally.

1 Introduction

Research on the biped robots constitutes one of the fascinating axes in robotics. Over the past several decades, several anthropomorphic robots have constructed. Some of them became well known even for non-specialists [1]-[5]. The prior target of researchers carried out in the field of biped robot attempts to solve the following problem: How to build a robot prototype able to walk as the humans are doing.

In the motion, one of the characteristics of the human walk is heel-contact and toe-off motions in steady walking. To implement adaptive walking, a foot is one of the most important regions of the human body in bipedal locomotion because it is a unique one that directly physically interacts with the environment. The human foot is the complicated structure which consists of many toes and joints. On the human walk, this structure not only makes ground reaction force smoothly change in the toe-off period but also equip foot with good adaption on uneven terrain.

From human foot inspiration, there have been some papers mentioned on the foot structure. For instance, Yu Ogura et al. have proposed the new foot mechanism by implement one passive joint for bending toe motion of Wabian-2R. However, in this study, the number of robot's DoF is reduced due to the predetermination is complemented by waist rolling motion [6]. Katsu Yamane et al. have investigated feet composed of curved surfaces at toe and heel and a flat section for a simple planar biped robot [7]. Shotaro Mamiya et al. have proposed a foot structure with point contact links to adapt to the ground surface with various geometry and hardness [8]. Sebastian Lohmeier et al. have designed a humanoid

robot LOLA with actively driven toe joints [9]. Kenji Hashimoto et al. have developed a human-like foot mechanism mimicking the medial longitudinal arch to clarify the function of the foot arch structure [10]. However, above mentioned papers mainly focus on the humanoid robot whose dimension is similar to human's one. The human-size robots are very convenient for designing structure and integrating actuator on foot.

By the contrary, a small robot has difficulty in building foot structure caused by limited dimension. Wooseok Choi et al. have developed a foot structure composed of a new toe mechanism with variable stiffness implemented using a leaf spring and rubber balls for a child-size humanoid robot. This structure can provide functionality and adaptability to humanoids locomotion on uneven terrains [11]. However, the spring stiffness range is still small. It does not reach the range of toe stiffness variation which is similar to human toes. Krissana Nerakae and Hiroshi Hasegawa have presented the foot mechanism with the big toe and tiptoe for a 10 DoF small biped robot. Nevertheless, in this work, the trajectories of corresponded joints on both legs are generated by seven isolated gait functions which make a gait pattern generation become complicated. Besides, the robot cannot walk naturally in comparison to human motion [12].

This study proposes a novel foot structure with toes for a small biped robot to cultivate its walking behavior on flat ground in the toe-off period. That enables the robot to walk stably and naturally. In toe mechanism, considering a reduction in the energy consumption, thus, the passive joint using torsion spring was selected as the toe joint. It can be said that its walking style, in

comparison to those of the other small biped robots, is more similar to that of a human.

The rest of this paper is organized in the following manner. Mechanical description of the robot is presented in Section 2. The principle of gait pattern generation is in Section 3. Section 4 shows the results of the development of the robot by dynamic simulation on ADAMS. Finally, Section 5 includes some brief conclusions and future works.

2 Experimental robot models

2.1 Overview of structural design

In this study, the proposed model is built based on the robot KHR-3HV of Kondo Kagaku Company which is the third generation of humanoid robots developed by this company. The robot KHV-3HV has the weight of 1.5kg, the height of 401.05mm and up to 22 DoF with 17 actual servos and 5 dummy servos. However, in the work, we concentrate on robot legs. Thus, upper body joints are fixed and lower body have 10 controlled joints for the legs as shown in Fig. 1.
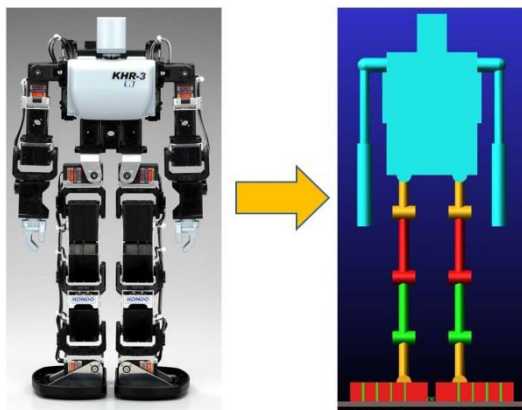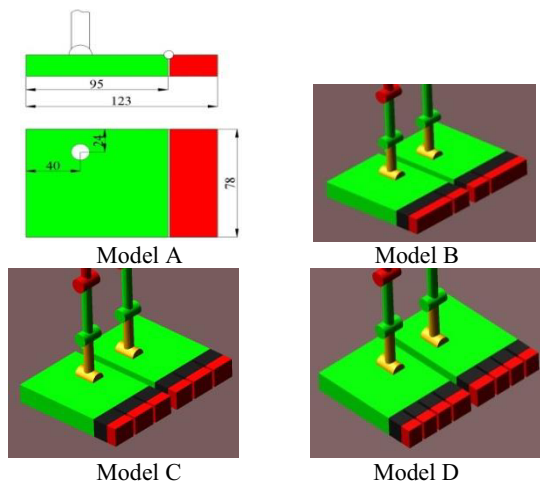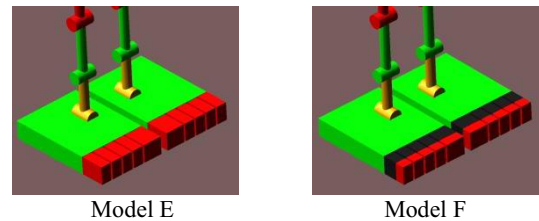

Figure 1. Real robot and proposed robot

Model A: Foot mechanism with tiptoe
Model B: Foot mechanism with two toes
Model C: Foot mechanism with three toes
Model D: Foot mechanism with four toes

Figure 2. Foot mechanism with toe
Model E: Foot mechanism with five rigid toes
Model F: Foot mechanism with five arthrogenous toes

2.2 Foot mechanism

During a stance phase of the human walk, support area continuously varies on the sole of the foot. At the end of toe-off, there is a phase switch from stance to swing. Toes have an important role in this process, it makes the phase switch smoother and more stable due to a decrease of the effect of the ground reaction force varied unexpectedly.

By this idea, we study the effect of the novel foot structure with toes on the locomotion of a small biped robot. The six toe mechanisms are designed for simulation experiments as depicted in Fig. 2.

In Fig. 2, model A shows the basic dimensions of the robot foot. In [13], Chockalingam et al. have proved that average ratio between the foot length and heel varies from 1.196 to 1.426. In this model, the length of heel and foot are 95mm and 123mm, respectively. Hence, the length of toes will be 28mm. The ankle joint position is determined based on the real robot. These dimensions are used to all remain models.

As proven in [12], the biped robot whose big toe width ratio per foot equals 0.28, has the longest walking distance when big toe length is fixed and this ratio is similar to the ratio of the human foot. Thus, the width of big toe and foot were designed of 22mm and 78mm. This ratio is applied to model B, C, D, E and F. Spring stiffness coefficients is respectively set of 0.52N.mm/deg, 0.26N.mm/deg to big toe joint and remain toe joints. For making the foot structure, two different types of material are used for heel and toes. Coefficients of static and kinetic friction are 0.5, 0.417 for heel and ground, 0.17, 0.155 for toes and ground, respectively.
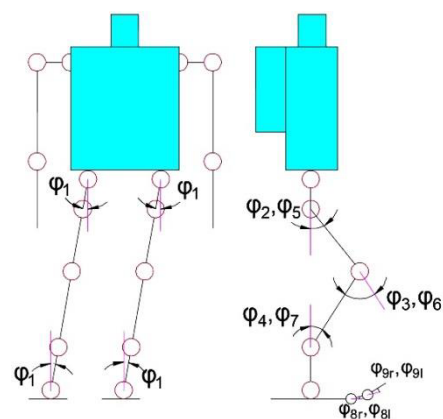

Figure 3. Definition of joint angles

3 Gait pattern generation

3.1 Definition of joint angle

The joint angles are defined as depicted in Fig. 3.

In Fig. 3, the hip, knee and ankle joints are active joints whose motion is supplied by the actuator. Toe joints designed by using torsion springs are passive joints. For model A and E, φ_{9r} and φ_{9l} are not used.

3.2 Gait function

Basing on the human walking pattern as depicted in [14], we assumed the robot control data was generated by the gait function as trigonometric function shown in Equation (1). By changing a, b, c, d coefficients, the gait functions will be created to allocate to each joint of the biped robot.

$$\varphi_i(t) = a_i + b_i.\cos(\omega t) + c_i.\sin(\omega t) + b_i.\cos(\omega t) \qquad (1)$$

where a, b, c, d are coefficients, t is time, ω is angular velocity and i is index of joint.

Gait functions are assigned to all joints as shown in Equation (2-8).

$$\varphi_1 = \begin{cases} 0, & t = 0 \text{ or } t = 3.6 \\ \pm 1.5, & t = 0.3 \text{ and } t = 3.3 \\ \varphi_1(t), & 0.3 < t < 3.3 \end{cases} \qquad (2)$$

$$\varphi_2 = \begin{cases} 0, & t \le 0.3 \text{ or } t \ge 3.6 \\ \varphi_2(t+0.6), & 0.3 < t < 3.3 \\ 15, & t = 3.3 \end{cases} \qquad (3)$$

$$\varphi_3 = \begin{cases} 0, & t \le 0.3 \text{ or } t \ge 3.6 \\ \varphi_3(t+0.6), & 0.3 < t < 3.3 \\ 30, & t = 3.3 \end{cases} \qquad (4)$$

$$\varphi_4 = \begin{cases} 0, & t \le 0.3 \text{ or } t \ge 3.6 \\ \varphi_4(t+0.6), & 0.3 < t < 3.3 \\ 15, & t = 3.3 \end{cases} \qquad (5)$$

$$\varphi_5 = \begin{cases} 0, & t = 0 \text{ or } t \ge 3.3 \\ 15, & t = 0.3 \\ \varphi_2(t), & 0.3 < t < 3.3 \end{cases} \qquad (6)$$

$$\varphi_6 = \begin{cases} 0, & t = 0 \text{ or } t \ge 3.3 \\ 30, & t = 0.3 \\ \varphi_3(t), & 0.3 < t < 3.3 \end{cases} \qquad (7)$$

$$\varphi_7 = \begin{cases} 0, & t = 0 \text{ or } t \ge 3.3 \\ 15, & t = 0.3 \\ \varphi_4(t), & 0.3 < t < 3.3 \end{cases} \qquad (8)$$

In toe mechanism, due to considering a reduction in the energy consumption of the robot, the passive joint was selected as toe joint. Consequently, φ_{8r}, φ_{8l}, φ_{9r} and φ_{9l} have values in the range from 0° to 30°; their values depend on the robot geometric posture as well as impact force when the robot walks.

4 Simulation result

In our experiments, the robot motion is simulated in three cycles. One cycle was set up to 1.2 seconds. Thus, three cycles spent on 3.6 seconds. Next, 1.2 seconds was used for checking robot stability. In this simulation, one step took 0.02 second, so the total number of steps was 240 steps. The simulation result is shown in Table 1.

Where X_f, Z_f, R_f are respectively sided distance, walking distance and angle of rotation at the final position of the robot.

The trajectory of the CoG point is depicted as in Fig. 4.

Table 1. Simulation result

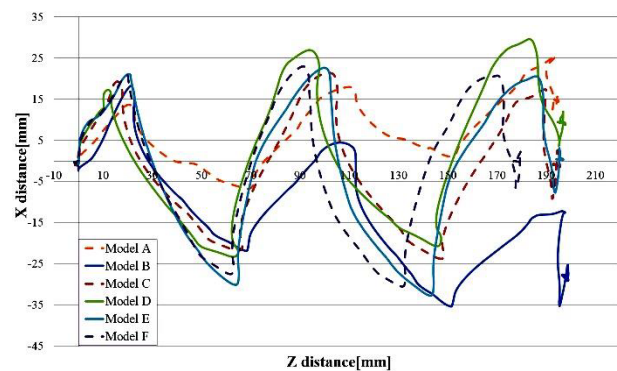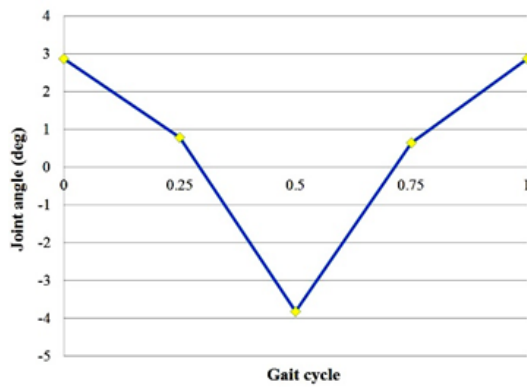| Model	Distance		Rotation
	X_f(mm)	Z_f(mm)	R_f(deg)
A	14.91	193.91	-5.867
B	-28.187	197.76	-9.557
C	-0.632	192.77	-2.795
D	9.350	195.31	1.309
E	0.384	195.19	2.998
F	-0.007	177.94	-0.091

Figure 4. Robot's CoG point trajectory

In Table 1 and Fig. 4, all the trajectory of the robot's CoG point is approximately the waveform of the circular function which is similar to that of the human's CoG point. Maximum walking distance is 197.76mm; side distance is -28.187mm in the case of the model B. This side distance is quite large. Thus, consideration of straight walking and stability, model E with X_f, Y_f, R_f of 0.384mm, 195.19mm and 2.998^o is the best model to do the research further.
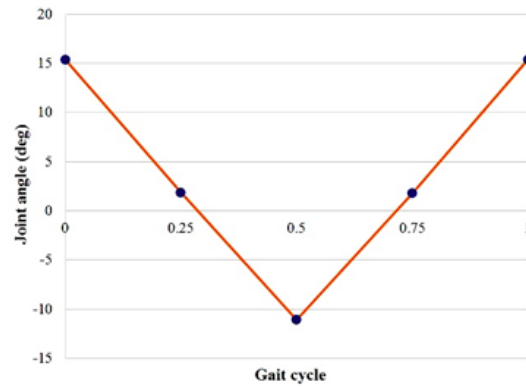
The waveform of the gait functions allocated to all joints of the biped robot is shown in Fig. 5.
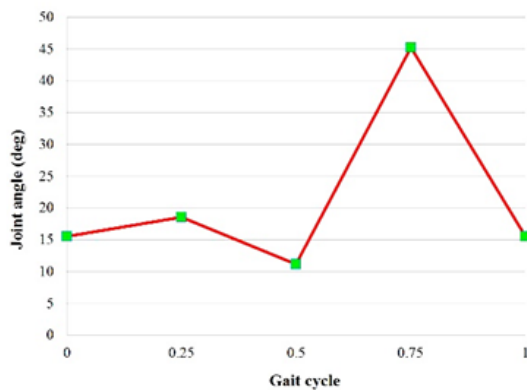
5 Conclusion

A novel foot structure with toes for the small biped robot is proposed in this paper. The locomotion of the robot is simulated on a flat plane by multi-body dynamics simulation software, ADAMS. In this work, we concentrate on the toe-off period of the biped robot in walk. As a result, all the models can walk stably with the bending of the toe which is similar to that of a human; model E obtains the best performance. Therefore, this model is selected for next research stages.
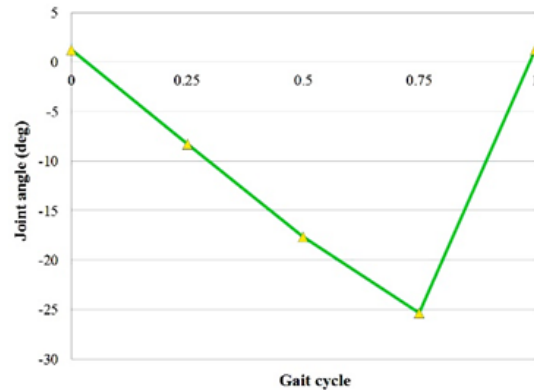
(a) A cycle of gait function (hip and ankle roll joint angle)

(b) A cycle of gait function (hip pitch joint angle)

(c) A cycle of gait function (knee pitch joint angle)

(d) A cycle of gait function (ankle pitch joint angle)

Figure 5. Waveform of the gait function

As for future work, we will try to consider the locomotion of the robot on rough ground, adjust spring stiffness to learn more. Besides, the foot structure of the model E will be also made and applied to the real robot.

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