Effect of Toe Length on Biped Walking Behavior

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***Abstract*—This paper presents the effect of toe length on the walking behavior of a humanoid robot. This research is conducted using the KHR-3HV, a humanoid robot manufactured by the Kondo Kagaku company. Research results show that toe length sensitively results in the change of the walking distance, lateral distance, as well as gait pattern. Robot locomotion is considered by varying the length of the toe through dynamic emulation using Adams software (MSC company, USA). Three response results, walking distance, lateral distance, and angle of rotation, are compared to identify the optimum toe length for the robot. The control data generated by a gait function as a trigonometric function can be used as reference data in the control process.**

***Index Terms*—humanoid robot, toe length, gait pattern, foot structure, locomotion**

I. Introduction

With the developments in science and technology, robots are ensured an indispensable role in human society. Their uses are motivated by many applications, such as support tasks, entertainment, or safety by replacing humans in dangerous tasks. However, walking remains one of the most challenging issues in the biped motion field. Biped walking requires that a humanoid robot perform steady and natural locomotion like human beings. This requirement is based on the need for safety and reliability when robots interact in daily human life.

A conventional approach to generate robot motion is based on the zero moment point (ZMP) and predefined foot trajectories [1]–[3]. Simultaneously, a controller is integrated to conserve balance in the presence of internal errors and external disturbances. Furthermore, the sole of the foot is used in parallel to the ground to make balancing easier.

However, human walking is a complicated process including three main phases in the stance period, as shown in Fig. 1. To perform this process, the human foot has a crucial role owing to its direct interaction with the ground.

Influenced by the human foot, recent research has concentrated on a robot foot structure. This is the most promising approach to improve robot walking behavior, because humanoid robots physically interact with the ground through the feet. These works achieved the primary success of enhancing the robot's walking gait to be a more human-like locomotion focusing on the heel strike and toe-off period. In particular, Kouchaki and Sadigh have considered the effect of toe-joint bending on biped gait performance [4]. Sadedel et al. added low-cost passive toe joints to the feet structure of the SURENA III humanoid robot; using passive toe joints reduced the energy consumption of ankle and knee joints in comparison with a similar toe-less robot [5]. In addition, a humanlike ankle-foot complex proposed by Narioka et al. [6] is designed to imitate the truss mechanism and the windlass mechanism of human beings. Hasegawa and Nerakae have proposed a foot structure consisting of a big toe and a tiptoe [7]. In our previous paper, we investigated the effect of ankle joint position on biped robot walking behavior on flat ground [8]. However, we considered that toe length also has a significant effect on robot walking gait and gait pattern function.

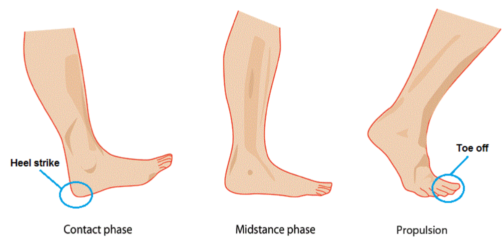

Figure 1. Human walking behavior in stance phase

Our purpose in this study is to determine the optimal toe length using the identical humanoid robot that was studied in our previous paper. All robot models are emulated within predefined lateral distance and angle of rotation constraints. The gait pattern data are created by an approximated optimization approach using response surface model (RSM) and improve self-adaptive differential evolution algorithm (ISADE).

This paper is organized in the following manner. A mechanical description of the robot is presented in Section II. The gait pattern generation method is introduced in Section III. Section IV shows the results of the development of the robot by dynamic simulation using Adams software. Finally, Section V includes brief conclusions and future works.

II. Experimental Model

A. Biped Robot Overview

In this study, the proposed model is based on the KHR-3HV robot manufactured by the Kondo Kagaku Company;

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KHR-3HV is the third generation humanoid robot developed by this company. The KHR-3HV robot weighs 1.5 kg, has a height of 401.05 mm, and has up to 22 degrees of freedom (DOFs) with 17 actual servos and five dummy servos. However, in our work, we only focus on the robot's legs. Thus, the upper body joints are fixed, and the lower body has 10 controlled joints for the legs, as shown in Fig. 2.

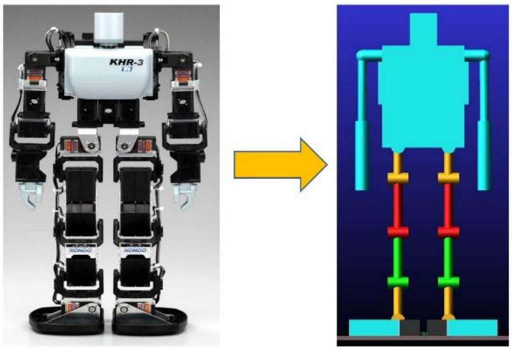


Figure 2. Robot and model

B. *Foot Structure Design*

During locomotion, the human foot support area continuously varies on the sole of each foot, as depicted in Fig. 3. The black areas are the locations where forces acting on the feet are supported. In detail, during stance phase, the loading response (LR) is heel only, mid stance (MSt) is foot flat, terminal stance (TSt) is forefoot and toes, and pre-swing (PSw) is medial forefoot. [9] found that toe contact with the ground varies considerably. The onset of toe involvement follows isolated forefoot support which occurs at 10% of the gait stance. In this period, toe pressures differ markedly with the greatest pressure occurring on the big toe. It ranged between 30 and 55% of the pressure at the heel. Thus, the big toe has an important role in human walking, especially during the toe-off period.

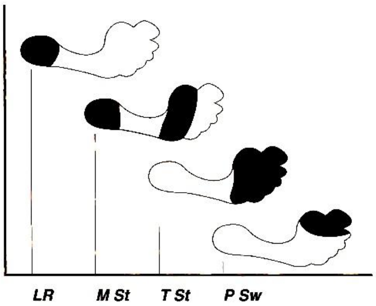


Figure 3. Sequence of foot support areas during stance [9]

By the above mentioned role of toe, Nerakae and Hasegawa have proposed a foot structure for enhancing the walking behavior of the biped robot [7], as depicted in Fig. 4, in which m and n are the length of toe and heel, respectively. Their study demonstrated that the big toe plays a significant role in supporting and transferring weight from one foot to another foot.

However, in their paper, the length of the toe is referred to ratio of human foot and is fixed. Our work is based on the assumption that this parameter has an effect on robot walking behavior, walking distance, and gait function because there is a significant difference of physical structure between KHR-3HV robot and human. The toe length parameter is considered in predefined ranges as described in Table I.

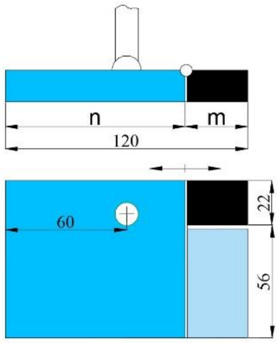


Figure 4. Robot foot structure

TABLE I. ROBOT TOE LENGTH PARAMETERS

No.	m(mm)	n(mm)	Ratio= m/(m + n)(%)
F1	8	112	6.67
F2	11	109	9.17
F3	14	106	11.67
F4	17	103	14.17
F5	20	100	16.67
F6	23	97	19.17
F7	26	94	21.67
F8	29	91	24.17
F9	32	88	26.67
F10	35	85	29.17

III. Gait Generation Method

A. *Joint Angle Definition*

The joint angles are defined as described in Fig. 5, and the range of the angle is based on human motion data as listed in Table II. This study supposes that the robot control data generated by the gait function is a trigonometric function, as shown in Eq. (1).

$$\varphi_i(t) = a_i + b_i.cos(\omega t) + c_i.sin(\omega t) + d_i.cos(2\omega t). \quad (1)$$

where φ_i is the angle of i joint, a, b, c, and d are coefficients, t is time, and ω is angular velocity. By changing a, b, c, and d coefficients, the gait function will be used to allocate movement to each joint of the robot.

Biped robot locomotion is presumed to be on flat ground with a total time duration of 4.8 s. Locomotion is simulated in three cycles with a total period of 3.6 s, and the remaining 1.2 s is used for checking robot stability. Each cycle is set to 1.2 s. As a result, the angular velocity is calculated by the below simple calculation. In the simulation, one step takes 0.02 s, and the total number of steps is 240. In the second cycle, the biped robot performs its motion the most naturally; hence, this cycle will be selected to show the waveform of the gait function as well as the robot walking behavior.

$\omega = \frac{2\Pi}{1.2} = 5.236.$

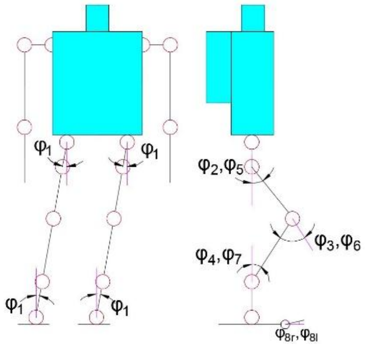


Figure 5. Robot joint angle definition

TABLE II. RANGE OF JOINT ANGLE

Angle	View plane	Leg	Joint	Value(°)
φ_1	Frontal	Both	Hip & Ankle	-15–15
φ_1	Sagittal	Right	Hip	-50–50
φ_3	Sagittal	Right	Knee	0–60
φ_4	Sagittal	Right	Ankle	-50–50
φ_5	Sagittal	Left	Hip	-50–50
φ_6	Sagittal	Left	Knee	0–60
φ_7	Sagittal	Left	Ankle	-50–50
φ_{8r}	Sagittal	Right	Proximal phalanx	0–30
φ_{8l}	Sagittal	Left	Distal phalanx	0–30

B. Optimization Procedure

Design variables (DVs):

$$x = [a_i, b_i, c_i, d_i],\ \mathrm{i} = 1 \div 4. \tag{2}$$

Constraint functions:

$$g_1(x) = 20 - |X_f| \geq 0. \tag{3}$$

$$g_2(x) = 5 - |R_f| \geq 0. \tag{4}$$

$$h_1(x) = 243.53 - Y_f = 0. \tag{5}$$

$$h_2(x) = N - 240 = 0, \tag{6}$$

where Z_f and X_f denote walking distance and lateral distance, respectively; R_f is the angle of rotation; Y_f is the distance from the center of mass (CoM) to the ground; and N is the number of simulation steps.

Objective function:

$$f(x) = -Z_f \rightarrow \min. \tag{7}$$

Penalty function:

$$P(x) = \sum_{i=1}^{2}\{\min[g_i(x), 0]\}^2 + \sum_{j=1}^{2}[h_j(x)]^2. \tag{8}$$

Modified objective function:

$$F(x) = -Z_f + \gamma P \rightarrow \min., \tag{9}$$

where a_i, b_i, c_i, d_i (i=1, 2, 3, 4) are coefficients of the gait function. There are four constraint functions. In Eq. (3)–(4), the X_f distance and R_f angle are constrained by ± 20 mm and ± 5°, respectively, to ensure that the biped robot can walk straight. In Eq. (5), Y_f must be equal to 243.53 mm to ensure that the robot does not slip and fall at the final framework. In Eq. (6), N is set to 240 for checking the success of the simulation. In Eq. (9), γ is a penalty coefficient set to 1000. Equations (3)–(6) will be checked again when the simulation finishes.

The optimization process is implemented by the following steps:

- Step 1. Initial design is initialized by specifying the simple analysis
- Step 2. Samples are simulated using Adams software
- Step 3. RSM is built
- Step 4. Design variables are optimized by the ISADE algorithm based on RSM
- Step 5. Design variables from Step 4 are used to check constraint functions again through the simulation
- Step 6. Convergence is checked; if achieved, the optimal process will be terminated. Otherwise, the process will repeat beginning at Step 2

IV. SIMULATION RESULTS

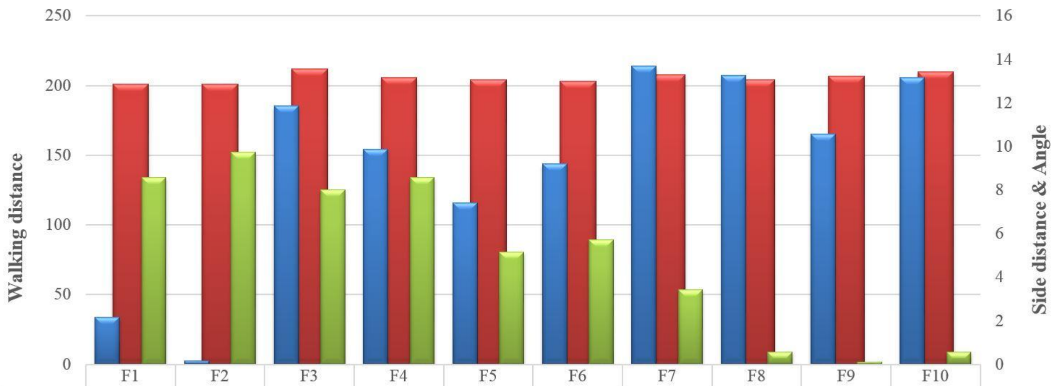
The results of the experiment are shown in Fig. 6.

The robot ankle joint trajectory in all experiments is shown in Fig. 7(a); the data are collected in the second cycle because the biped robot performs the most natural and stable locomotion in this period. By comparison, the human ankle joint trajectory is depicted in Fig. 7(b); the subject in this experiment was a man. He was 33 years old, 164 cm in height, and weighed 49.5 kg. While the subject was walking, the kinematic data for the lower body were captured by a motion capture system, and data were recorded at a sampling rate of 200 Hz.

As can be seen in Fig. 7, in general, the robot ankle joint trajectory has a trend similar to that of a human. From F1 to F10, the height of the ankle joint trajectory changes to adapt to the length of the toe. The F5 model with the ratio of 16.67% has the best performance, which is the most comparable to the human ankle joint trajectory. Thus, this toe length is selected.

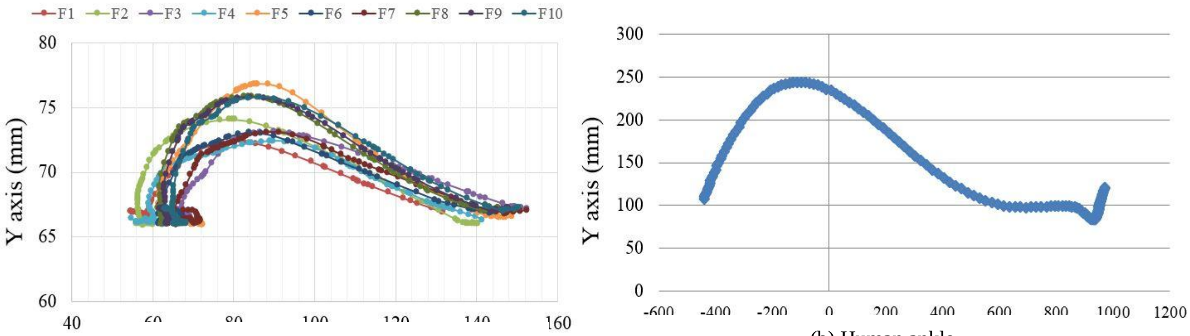
The comparison of gait function waveforms for all joints is depicted in Fig. 8.

When the toe length is changed from F1 to F10, as described in Table I, there is a significant change in the knee and ankle joint angles in a gait cycle, as depicted in Fig. 8(c) and (d). The other joint angles remain almost constant or the change is small. To be specific, hip roll and pitch joint angles only have a negligible change at 0, 0.5, and 1 in a gait cycle, as shown in Fig. 8(a) and (b). Fig. 6 shows that the F5 model performance is the best result. Thus, this model should be selected for research in the future.



	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10
Zd(mm)	201	201	212	206	204	203	208	204	207	210
|Xd|(mm)	2.18	0.16	11.87	9.88	7.43	9.2	13.69	13.26	10.58	13.17
|Rd|(deg)	8.59	9.74	8.02	8.59	5.16	5.73	3.44	0.57	0.11	0.57

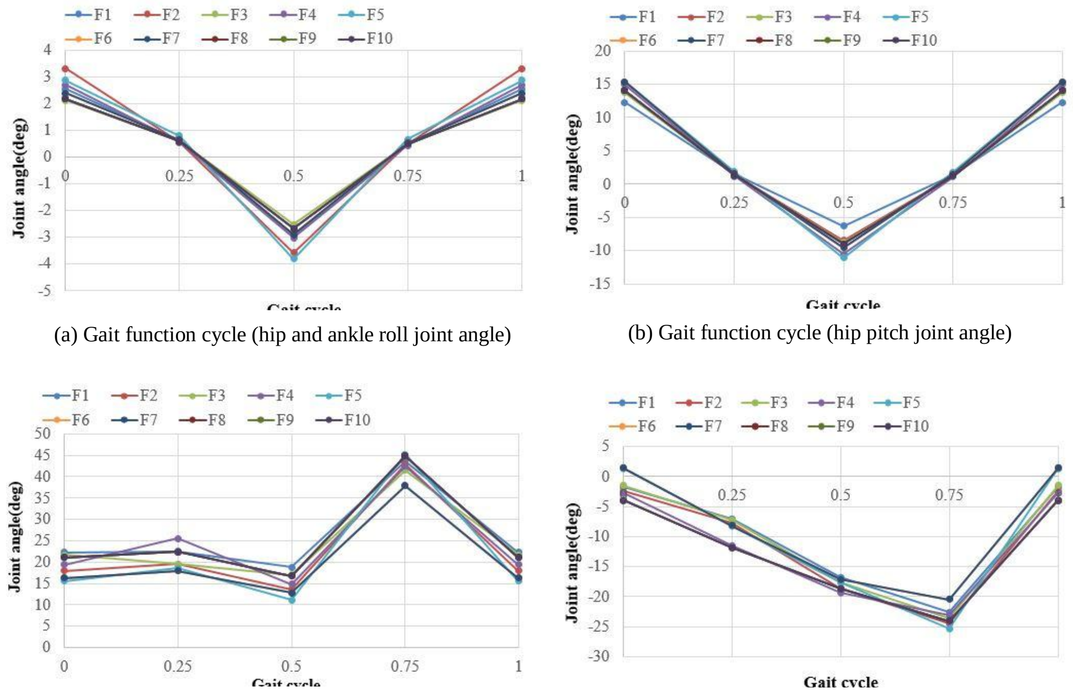
Figure 6. Experiment results



(a) Robot ankle

(b) Human ankle

Figure 7. Ankle joint trajectories in a cycle



(a) Gait function cycle (hip and ankle roll joint angle)

(b) Gait function cycle (hip pitch joint angle)

(c) Gait function cycle (knee pitch joint angle)

(d) Gait function cycle (ankle pitch joint angle)

Figure 8. Gait function waveforms

V. CONCLUSIONS

The toe is an important factor in enhancing biped walking behavior with respect to human walking, especially during the toe-off period. In this study, we consider the length of the toe and its significant effect on the locomotion performance as well as gait pattern of the humanoid robot. All the designed models with changing the length of the toe are simulated in Adams software environment. Through the simulation, all the models can walk straight and stay within the constraint conditions. In addition, the gait functions are successfully generated by the approximated optimization method for each model. The ankle joint trajectory of the robot is compared with that of the human to identify the optimum length for the robot's toe. To the end, the results show that the optimum ratio of the toe for the proposed robot is 16.67%.

In a future work, the authors plan to design a real robot and consider its locomotion on rough ground.

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