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Human-like Walking with Knee Stretched, Heel-contact and Toe-off Motion by a Humanoid Robot

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***Abstract* - A humanoid robot, WABIAN-2R, capable of human-like walk with stretched knees and heel-contact and toe-off motions is proposed in this paper. WABIAN-2R has two 1-DOF passive joints in its feet to enable it to bend its toes in steady walking. Further, it has two 6-DOF legs, a 2-DOF pelvis, a 2-DOF trunk, two 7-DOF arms with 3-DOF hands, and a 3-DOF neck. In addition, a new algorithm for generating walking patterns with stretched knees and heel-contact and toe-off motions based on the ZMP criterion is described. In this pattern generation, some parameters of the foot trajectories of a biped robot are optimized by using a genetic algorithm in order to generate a continuous and smooth leg motion. Software simulations and walking experiments are conducted, and the effectiveness of the pattern generation and mechanism of WABIAN-2R, which have the ability to realize more human-like walking styles in a humanoid robot, are confirmed.**

Index Terms - Robot Design, Humanoid Robot, Biped Robot, Stretch Walking, Heel-contact and toe-off motions

I. INTRODUCTION

In recent times, many research groups have studied biped humanoid robots to realize robots that are capable of coexisting with humans and performing a number of different tasks. For example, a HONDA research group has developed the humanoid robots P2, P3, and ASIMO [1]. The Japanese National Institute of Advanced Industrial Science and Technology (AIST) and Kawada Industries, Inc. have developed HRP-2P [2][3]. The University of Tokyo has built the H6 and H7 [4][5], and the Technical University of Munich has developed JOHNNIE [6]. Waseda University has developed the WABIAN series, which realizes humanoid walking with 3-DOF trunk motion and walking with 3-axis ZMP (zero moment point) compensation using the trunk [7][8]. The Korea Advanced Institute of Science and Technology (KAIST) has developed a 41-DOF humanoid robot KHR-2 [9].

The abovementioned human-size biped robots have realized stable and dynamic walking. If these humanoid robots were capable of using rehabilitation or welfare instruments, they could be useful systems for quantitative measurements of effectiveness of such instruments. Therefore, we, the Waseda University research group, have proposed the use of a biped humanoid robot as a human motion simulator; where a biped humanoid robot having an ability to mimic various human motions is used for testing welfare/rehabilitation instruments. If the humanoid robot uses such instruments as similar as a human does, it can provide quantitatively information (with some sensor mounted on the robot) about the effectiveness of the welfare/rehabilitation machine.

Such simulations require a humanoid robot that is considerably similar to humans in terms of its mechanism and motion pattern. However, it cannot be said with certainty that humanoid robots developed in recent studies realize a "human-like" walk. Almost all humanoid robots, such as those mentioned above, walk with a constant waist height and with their knees bent. The ability to walk with stretched knees is an important quality that a humanoid robot should possess in order for it to mimic human motion. Therefore, prior to this study, we have already developed a new biped walking robot named WABIAN-2 (WAseda BIpedal humANoid-2) based on the development of WABIAN-2/LL (WAseda BIpedal humANoid-2 Lower Limb)[10][11][12].

WABIAN-2 achieves a more human-like walk than the other humanoid robots because it can stretch out its knees avoiding the singularity by using waist motion, while walking. However, there is a difference between the walking styles of WABIAN-2 and humans. One of the characteristics of human walk is heel-contact and toe-off motions in steady walking. Thus, if the robot realizes not only walking with stretched knees but also heel-contact and toe-off motions, it can be said that its walking style, in comparison to those of other humanoid robots, is more similar to that of humans.

In this paper, first, the mechanical description of WABIAN-2R (WAseda BIpedal humANoid-2 Refined), which has a 6-DOF active joint for each leg and one passive DOF in the foot, is described. Next, the principle of the pattern generation for stretched knee and heel-contact and toe-off motions is presented. Lastly, the effectiveness of the development of the humanoid robot is confirmed by software simulations and walking experiments.

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II. Mechanical Description of WABIAN-2

A. Overview of mechanical design

Figure 1 presents the DOF configuration of the new humanoid robot. In this study, the initial pose of the robot is defined as one in which it is standing straight, and the rotational direction of each joint is defined by using the inertial coordinate system fixed on the ground, as shown in Fig. 1.

Wabian-2R has two 6-DOF legs, a 2-DOF waist, a 2-DOF trunk, two 7-DOF arms, a 3-DOF neck, and two 3-DOF hands. In the 2-DOF waist system, the roll axis and yaw axis should be perpendicular to each other, and they should cross the middle point between the two hip joints. This will result in minimizing the displacement of the trunk by waist motion and simplifying the kinematics calculation. In addition, the roll joint should be positioned on the lower limb side and the yaw joint on the trunk side. This makes the yaw joint capable of being used in yaw rotation of both the hips and the trunk. These DOF configurations of the waist and trunk enable substantial 3-DOF trunk motions.

The frameworks of WABIAN-2 are mainly made of duralumin in order to realize antithetical concepts: light weight, high stiffness, and wide movable range. Each actuator system of the joints comprises a DC motor, a harmonic drive gear, a lug belt, and two pulleys. This double speed reduction mechanism allows a high reduction ratio and also enables a joint axis to be set apart from a motor axis. This mechanism provides designs for a human-like joint mechanism without a large projection. In this paper, we mainly focus on the development of the waist, trunk, and arms. Figure 2 presents a photo of WABIAN-2. The specifications of each joint, such as the maximum torque and rotating speed, are designed based on the results of software simulations. These results were computed by using Newton-Euler's method and the estimated mass distribution. Several types of simulations were carried out to determine the joint specification.

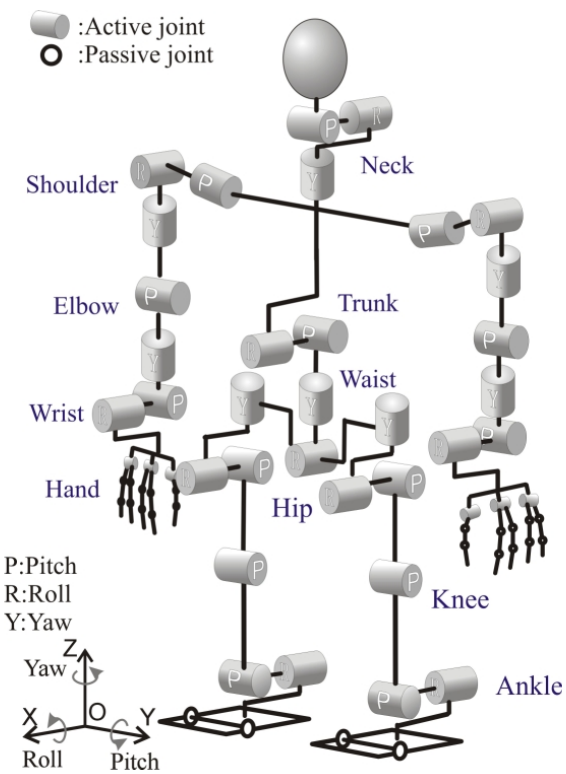


Figure 1. DOF configuration of WABIAN-2R

B. Foot mechanism

Figure 3 shows the new foot mechanism of WABIAN-2R. The foot has one passive joint for bending toe motion. The passive joint was selected as the toe joint based on human gait analysis reports; many researchers mention that a human usually walks with heel-contact and toe-off motions in steady walking. In this case, the toe muscles are relaxed and the power for toe motion is seldom supplied to these muscles. Therefore, a mechanical model of the foot in steady walking will be one in which the foot has one passive hinge joint.

The length of the foot is 202.0 mm, and the length of the toe is 48.5 mm. The movable angle of the toe is 71.7 deg. The curve of the heel is designed in order that the heel contact on a floor with an angle between 0 and 40 deg. The frameworks of the foot are made of CFRP (carbon fiber reinforced plastic) by sandwiching honeycomb structural bodies of thin aluminum plates. In addition, a 6-axis force/torque sensor is mounted on

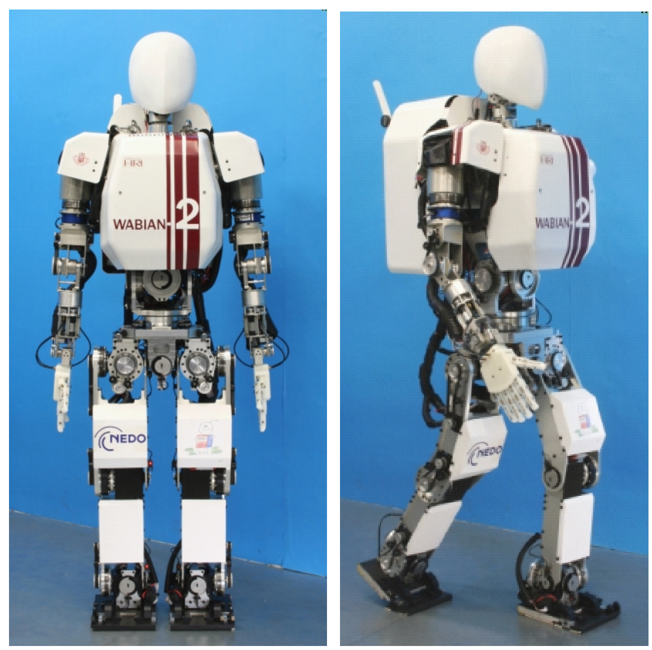
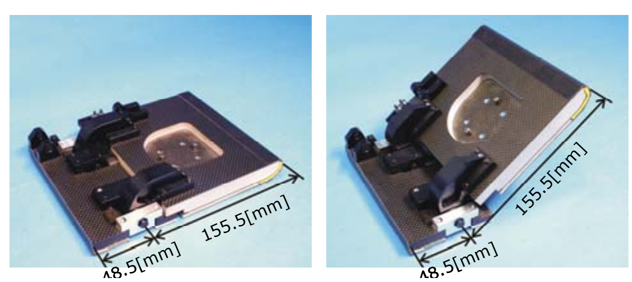


Figure 2. Photos of WABIAN-2



(a) initial (b) bent

Figure 3. Foot mechanism

the foot to measure the ZMP, reaction forces, and so on.

III. PATTERN GENERATION

A. *Walking pattern with legs stretched*

We have developed an algorithm that enables a biped humanoid robot to stretch its legs [11]. The essential features of the stretch walking pattern generation are listed below.

1) A trajectory for the knee joint in each leg is predetermined as one of the initial walking parameters.
2) The height of the waist is not predetermined; it depends on the other parameters.
3) A reduction in the number of DOFs due to the predetermination is complemented by waist rolling and/or yawing motion.

In this pattern generation method, the knee trajectories are set using cubic spline functions that follow continuous and differential trajectories. Further, these functions simplify the generation of such trajectories by selecting some point on the trajectory. Walking patterns with various gaits are generated by setting different knee trajectories.

B. *Foot trajectory*

To set a continuous foot trajectory $\mathbf{X}_{foot}$ in one step taken by the robot, the trajectory is divided into three phases: a toe-off phase, swing phase, and heel-contact phase. The toe-off phase is the intermediate phase between heel lift-off and toe lift-off. The swing phase is the intermediate phase between toe lift-off and heel touch down on the floor after the foot swings. The heel-contact phase is the intermediate phase between heel touch down on the floor and the touch down of the entire foot sole on the floor.

The toe-off phase has five parameters: the six-dimensional posture matrixes of the foot, $\mathbf{X}_{start}$, $\dot{\mathbf{X}}_{start}$, $\ddot{\mathbf{X}}_{start} \in R^6$, when the foot sole is on the floor before the foot rises; the angle with the floor θ_{toe} ; and the angular velocity ω_{toe} at toe lift-off. The heel-contact phase also has five similar parameters: the six-dimensional posture matrixes of the foot, $\mathbf{X}_{end}$, $\dot{\mathbf{X}}_{end}$, $\ddot{\mathbf{X}}_{end} \in R^6$, when the foot sole is on the floor; the angle with the floor θ_{toe} ; and the angular velocity ω_{toe} when the heel starts to touch the floor. The manner in which the foot lifts in the swing phase is determined using the middle posture $\mathbf{X}_{mid}$. The continuous foot trajectory is generated to connect the three phases by using a polynomial interpolation function. Figure 4 shows an illustration describing the three phases and the parameters.

C. *Optimization of walking parameters for heel-contact and toe-off motions*

In the pattern generation process described above, many walking parameters can be set in order to generate various

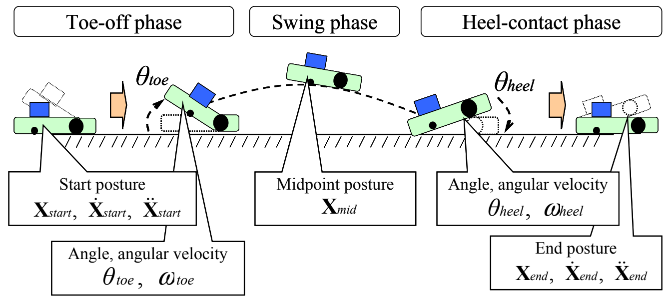


Figure 4 Parameters for foot trajectory

motions required by robot users. However, the optimization of the parameters is required. The purpose of this study is the realization of human-like walk with stretched knees and heel-contact and to-off motions in a humanoid robot. The optimization method can be described as follows.

Figure 5 shows an illustration to describe the walking parameters from the DOF viewpoint. Generally, a biped robot must have a 2-DOF compensatory motion to maintain its balance according to the ZMP trajectory. If the robot compensates the ZMP using its waist trajectory, the 2-DOF horizontal motions x_{waist} , y_{waist} must be controllable. The knee angle trajectories are also predetermined and the waist height z_{waist} and waist rolling θ_{roll} are not set in the stretch walking pattern generation mentioned above. Moreover, waist pitching θ_{pitch} , yawing θ_{yaw} , and foot trajectory $\mathbf{X}_{foot}$ must be considered as optimizable parameters. θ_{pitch} does not control lower limb motion in this DOF configuration. Therefore, in this study, the elements of $\mathbf{X}_{foot}$ —θ_{toe} , ω_{toe} , θ_{heel} , ω_{heel} , and θ_{yaw} —are considered as optimized parameters for continuous walking with heel-contact and toe-off motions.

Human gait analysis researchers have reported that normal people lift their heel from the floor within 10 ms and subsequently rotate their toe after heel touch down on the floor within 10 ms[14]. In order to generate continuous walking patterns with heel-contact and toe-off motions, the continuity of the vertical motion of the leg must be considered because heel-contact and toe-off motions are performed within a short time. Therefore, in this study, an evaluation function that focuses on waist rolling, hip joint pitching, and ankle pitching is set as follows:

$$F = w_1 \cdot \max \theta_{w\_r} + w_2 \cdot \max \dot{\theta}_{w\_r} + w_3 \cdot \max \dot{\theta}_{th\_p} + w_4 \cdot \max \dot{\theta}_{ak\_p} \quad (1)$$

, where

θ_{w_r} : *Waist Roll Angle* $\dot{\theta}_{w\_r}$: *Waist Roll Angle Velocity*

$\dot{\theta}_{th\_p}$: *Hip Pitch Angle Velocity* $\dot{\theta}_{ak\_p}$: *Ankle Pitch Angle Velocity*

w_{1-4} : *weighting fuctor.*

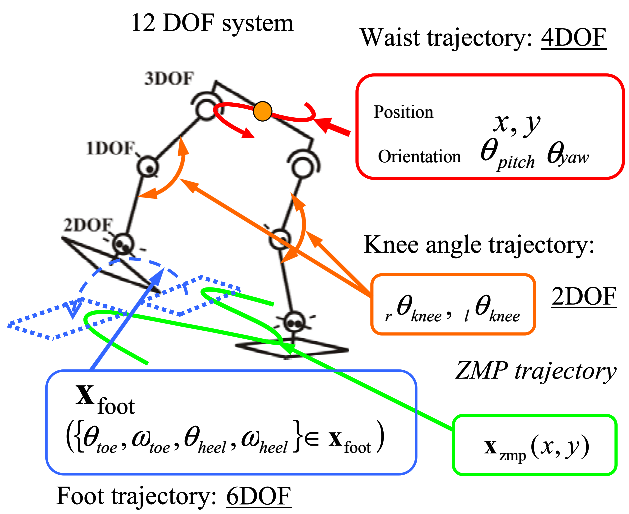


Figure 5 Walking parameters

To find the minimum F, a continuous trajectory with a small change in the angular velocity is obtained. In this paper, a genetic algorithm is used for searching the minimum F.

D. Algorithm implementation

A dynamic walking pattern according to a ZMP trajectory for contacting feet requires a motion that compensates ZMP, such as a moving waist, waving arms or upper body, and so on. In this study, the compensatory walking motion will be generated in accordance with the horizontal waist motion. An overview of the pattern generation can be described as follows.

1) Trajectories for the feet and waist are set. A ZMP trajectory is planned in the support polygon formed between the contacting foot and the ground.

2) The moments generated by the motion of the lower limbs and the upper body along the planned ZMP trajectory are computed using the Newton-Euler equation.

3) The horizontal waist motion to compensate for the moments is computed using the linearized biped model.

4) A whole body motion based on the compensatory waist motion is computed using inverse kinematics.

5) In order to obtain the exact solution, this calculation is repeated.

In this case, the pattern generation requires the repeat calculation to solve the waist horizontal trajectory that compensates the ZMP trajectory. This modification of the waist trajectory by the repeat calculation effects the calculation of the joint trajectories including $\theta_{w\_r}, \dot{\theta}_{th\_p}, \dot{\theta}_{ak\_p}$ and so on. In fact, if a foot trajectory $\mathbf{X}_{foot}$ is optimized by using the evaluation function and a walking pattern with the $\mathbf{X}_{foot}$ and the modified waist trajectory is generated, the walking pattern is not always possible to be a continuous pattern with a small change in the angular velocity. Therefore, the pattern generation should have a function to recheck the adequacy of the value of F. Figure 6 shows the pattern generation algorithm flow.

IV. Experiments

A. Software simulation

Software simulations of the pattern generation method were carried out in order to confirm and verify the pattern generated. Figure 7 shows the stick diagrams of the walking pattern: (a) conventional walking style, which is the earlier walking style with a constant waist height and knees bent at all times; (b) stretch walking using predetermined knee trajectories to imitate human gait without heel-contact and toe-off motions; and (c) stretch walking with the same knee trajectories mentioned above and heel-contact and toe-off motion. Stick diagram (d) depicts human gait [13]. A comparison of these diagrams reveals that stick diagram (c) is the most analogous to human gait (d).

B. Walking experiments

Walking experiments with/without heel-contact and toe-off motions were carried out in the following order on a horizontal flat plane by using WABIAN-2R: (i) the conventional walking style, Fig. 7(a); (ii) stretch walking style, Fig. 7(b); and (iii) stretch walking style with heel-

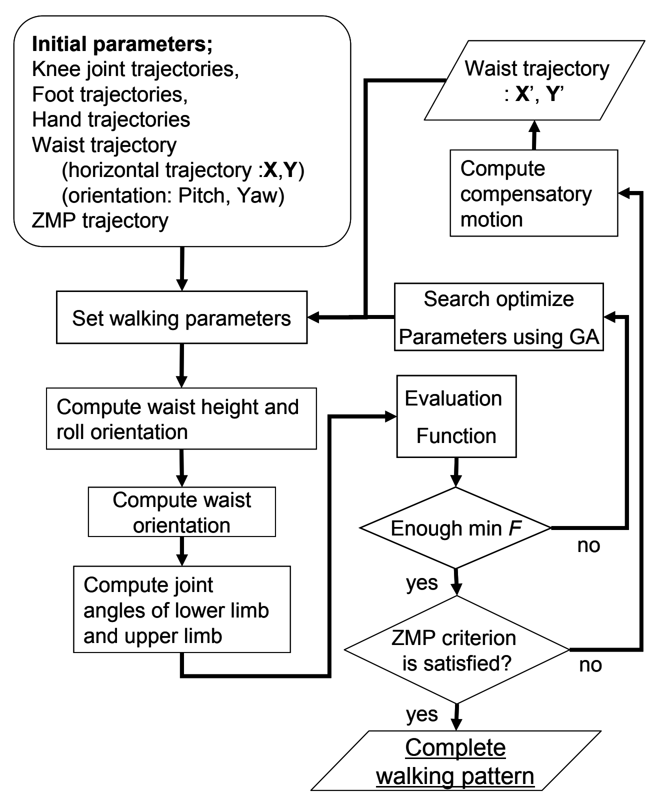


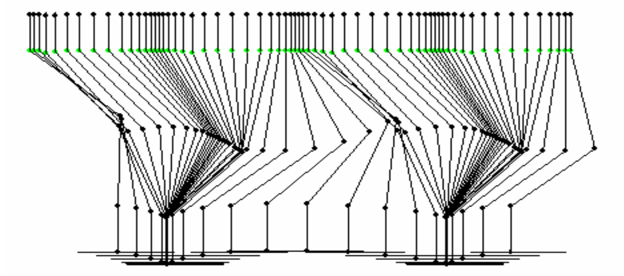
Figure 6 Pattern generation

contact and toe-off motions, Fig.7(c).

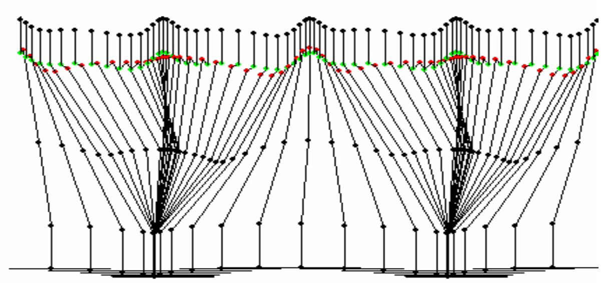
The experiments were carried out with a step cycle of 0.96 s/step, step height of 0.03 m, and five different step lengths from 0.00 m to 0.50 m in increments of 0.05 m. In the case of stretch walking with heel-contact and toe-off motions, the results showed that stable walking can be performed within all step lengths. Figure 8 shows a scene of the walking experiment with a step length of 0.50 m/step.

C. Discussion

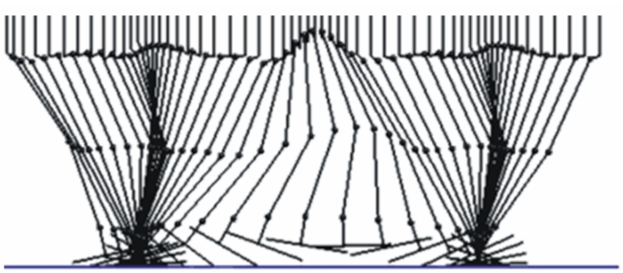
To compare the three walking styles with the human walking style, measurements of the vertical ground reaction force (GRF) applied to the 6-axis force sensor on the foot were carried out. Figure 9 shows the results for the right foot in each walking cycle in steady walking. The measurements for a human (Fig. 9(d)) were carried out by using force plates. In the case of the conventional walking style, substantially constant vertical forces are applied in the support phase. On the other hand, the result of the stretch walking shows double peaks of the vertical forces, similar to the measurements for humans. Furthermore, considering that the second peak is higher than the first one, it is said that the results of stretch walking with heel-contact and toe off motions are most similar to the human walking style.



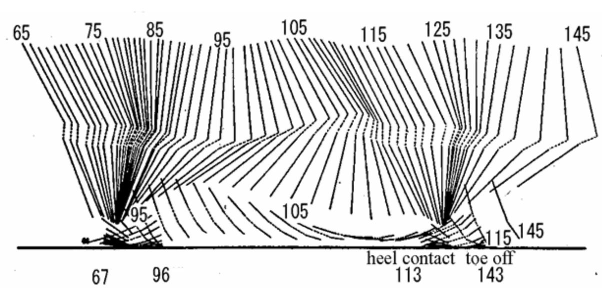
a) Conventional walking



b) Stretch walking without heel-contact and toe-off motion



c) Stretch walking with heel-contact and toe-off motion



d) Human walk

Figure 7. Stick diagrams

V CONCLUSION AND FUTURE WORK

This paper describes a humanoid robot WABIAN-2R capable of human-like walk with stretched knees and heel-contact and toe-off motions. WABIAN-2R has two 1-DOF passive joint in its feet to enable it to bend its toes in steady walking. Further, it has two 6-DOF legs, a 2-DOF pelvis, a 2-DOF trunk, two 7-DOF arms with 3-DOF hands, and a 3-DOF neck. In addition, a new algorithm for generating walking patterns with stretched knees and heel-contact and toe-off motions based on the ZMP criterion is described. In this pattern generation, some parameters of the foot trajectories of a biped robot are optimized by using a genetic algorithm in order to generate a continuous and smooth leg motion. Software simulations and walking experiments are conducted, and the effectiveness of the pattern generation and mechanism of WABIAN-2R that have the ability to realize more human-like walking styles in a humanoid robot are confirmed. In the walking experiments, WABIAN-2 realized stable walking up to 0.50 m at 0.96 s/step.

In the near future, a hardware simulator system capable of being applied for the evaluation of welfare machines or robots

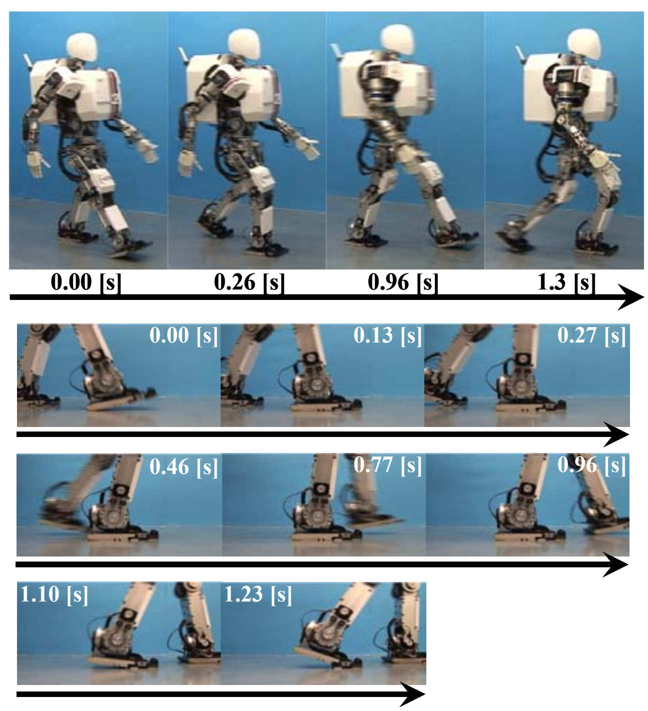
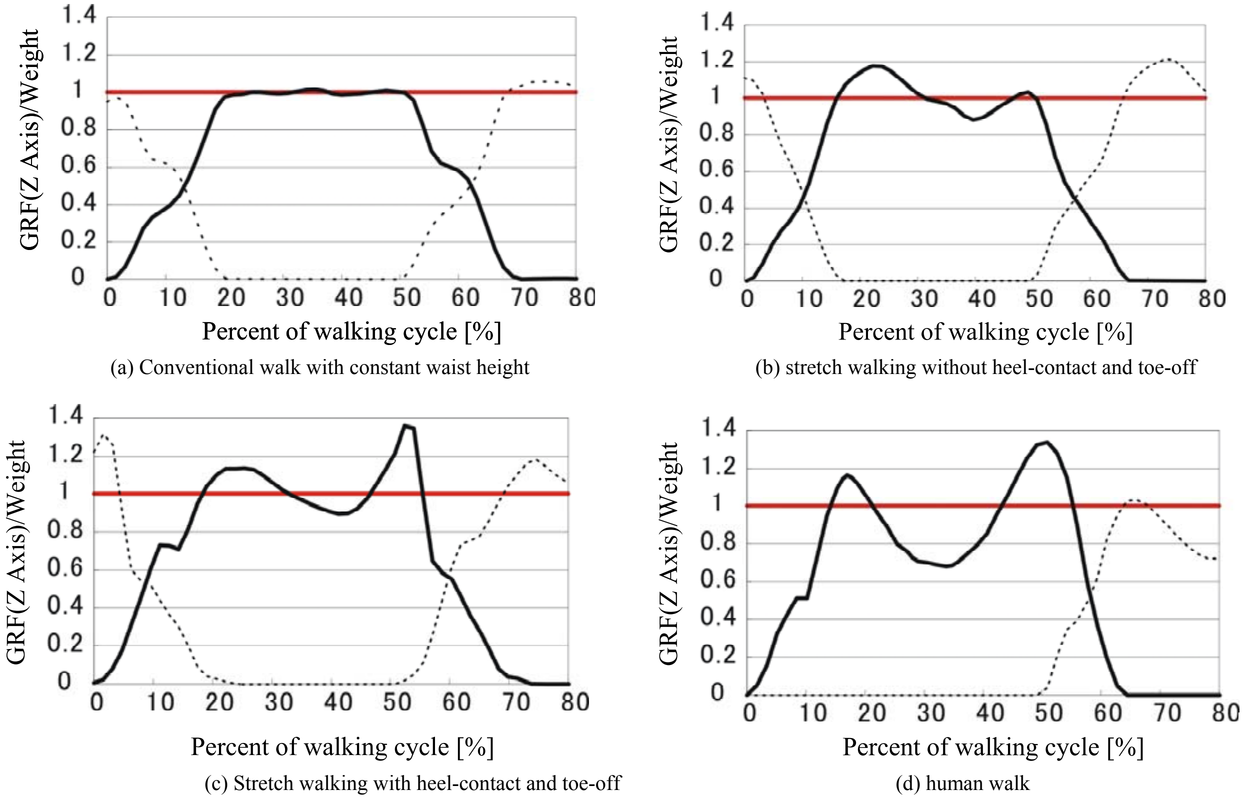


Figure. 8 Walking motion of WABIAN-2R



(a) Conventional walk with constant waist height

(b) stretch walking without heel-contact and toe-off

(c) Stretch walking with heel-contact and toe-off

(d) human walk

Figure 9. Results of vertical Ground Reaction Force

shall be proposed. Moreover, the effectiveness of this proposal shall be experimentally verified.

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