Application of Biped Humanoid Robot to Motion Simulation for Elderly and Disabled People

Hideki Kondo, Yu Ogura, Hiroyuki Aikawa, Akitoshi Morishima, Juri Shimizu, Hun-ok Lim, and Atsuo Takanishi, *Graduate School of Advanced Science and Engineering, Waseda University*

***Abstract*— the goal of this study is to realize 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 apparatuses. In this paper, a humanoid robot, WABIAN-2R, capable of not only human-like walking but also the emulation of disabled persons' walking is proposed. It has two 6-DOF legs, two 1-passive-DOF feet, a 2-DOF pelvis, a 2-DOF trunk, two 7-DOF arms with 3-DOF hands, and a 3-DOF neck. In addition, an algorithm for generating walking patterns for emulations of disabled persons' gaits for each case of disabilities based on the ZMP criterion is described. Finally, authors report a walking experiment with a walk-assist machine and an emulation of hemiplegic gait to verify the availability of the human motion simulator.**

I. INTRODUCTION

In Japan, due to the effect of the aging society, seniors and disable persons (in particular, for lower limb) are becoming a big problem to be seriously considered. Therefore, it is required to develop more effective welfare apparatuses for the elderly and disabled. However, it is difficult to evaluate them by anthropometric because of the problems on the safety in experimental subjects and the measurement accuracy.

Accordingly, authors have proposed an application of a biped humanoid robot to a human motion simulator. This application technique will proved us with safe and quantitative evaluation of welfare apparatuses. The advantages of our approach are as follows:

(1) The angle and torque at the each joint can be easily measured
(2) Several experiments testing the instruments can be performed without injuring any person.
(3) Various kinds of paralytic's walking patterns can be easily simulated.

Although we want the human motion simulator to be applied to various kinds of the instruments, as the first approach, we focused on walk-assist machine. However, the conventional robots mentioned above can only walk with the knees bent and the constant height of the waist. Such walk motion restricts the simulation of human motion.

Until now, authors have developed a new humanoid robot, WABIAN-2R (WAseda BIpedal humANoid No.2 Refined) and realized human-like walking with the knees stretched, heel-contact and toe-off motion [16]. In this paper, authors report a walking experiment with a walk-assist machine and an emulation of hemiplegic gait to verify the availability of the human motion simulator.

This paper is organized as follows; at first, we describe the design concept of our humanoid robot. Then, a walking pattern generation method is introduced which enables the robot to stretch its knees. Furthermore, we describe the algorithm of a pattern generation for mimicking a disabled person's gait. Finally, two experiments and the results are presented to demonstrate the feasibility of using the robot as a human motion simulator. In the first experiment, we verified if the use of a robot as a human simulator may provide us quantitative data for the assessment of a walk-assist machine. In the second one, the emulation experiment of the hemiplegic gait of a subject was conducted to demonstrate the effectiveness of the pattern generation method.

II. HARDWARE MECHANISM

A. Design of the Hardware

We developed the new humanoid robot as a human motion simulator, WABIAN-2R (Fig. 1 (a)). The robot has two 6-DOF legs, two 1-passive-DOF feet, a 2-DOF waist, a 2-DOF trunk, two 7-DOF arms, two 3-DOF hands and a 3-DOF neck to replicate various human motions and gave all of the joints the movable range as similar as possible to the human ones. Fig. 1 (b) shows the DOF configuration. The frameworks of the robot were made of duralumin having both light weight and high stiffness. The length of each link is determined by reference to data of adult women.

There is an actuation system composed by a DC motor, a harmonic drive gear, a timing belt and two pulleys at each joint. The performance of each joint such as maximum torque and rotational speed was determined by software simulations.

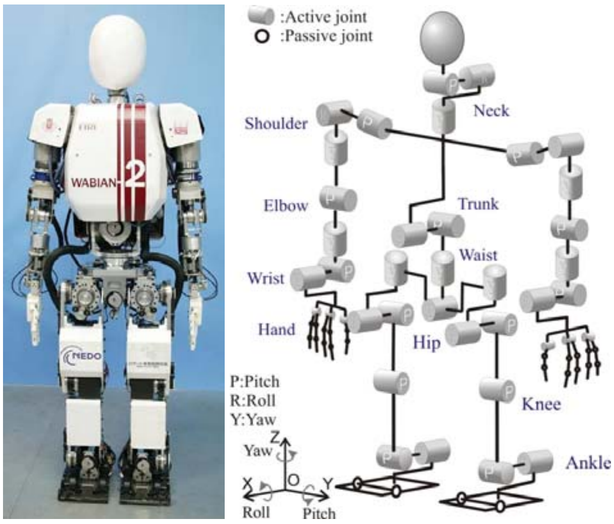
B. Measuring Method

We can obtain the energy consumption at each joint, measuring the motor current by an ammeter which includes an electrical governor on the motor driver. Furthermore, WABIAN-2R has 6-axis force/torque sensors at both the ankles and upper arms. Using the sensor installed between each ankle and foot, we can measure the floor reaction forces (FRF) and ZMP. The reaction forces from the walk-assist machine can be measured from the sensor

Hideki Kondo, Akitoshi Morishima, Yu Ogura, Kazushi Shimomura, Shimpei Momoki, Juri Shimizu are students in the Graduate School of Advanced Science and Engineering, Waseda University (e-mail: kondo_hideki@asagi.waseda.jp)

Hun-ok Lim is a professor in the Department of Mechanical Engineering, Kanagawa Univ. and a member of the HRI (Humanoid Robotics Institute), Waseda Univ. (e-mail: holim@ieee.org)

Atsuo Takanishi is a professor in the Department of Mechanical Engineering, Waseda Univ. and one of the core members of the HRI, Waseda Univ. (e-mail: takanisi@waseda.jp)



(a) (b)

Fig. 1. Photo and DOF configuration of WABIAN-2R

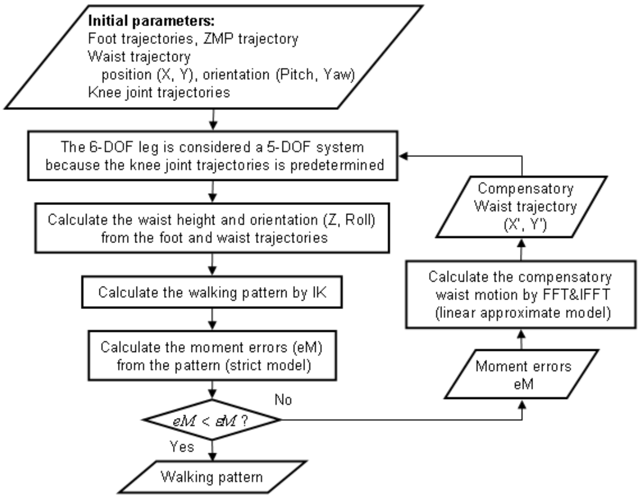


Fig. 2. Walking pattern generation

installed at each upper arm.

III. WALKING PATTERN GENERATION

A. Walking Pattern with the Knees Stretched

A conventional biped humanoid robot generally walks with its knees bent. However, the walking is not good enough for simulating human motions. Therefore, we have developed a walking pattern generator for WABIAN-2R to walk with the knees stretched [14], [15].

A dynamic walking is realized by generating walking pattern which consists of time-series angle data for all of the joints and making the joints move in accordance with the pattern. When a walking pattern is generated, various kinds of walking are feasible by determining redundant walking parameters which define the walking. Here are the parameters;

- Trajectories of the feet (position and attitude)
- Trajectories of the hands (position and attitude)
- ZMP trajectory (x_{zmp}, y_{zmp})
- Trajectory of the waist ($x_w, y_w, z_w, \theta_{w\_roll}, \theta_{w\_pitch}, \theta_{w\_yaw}$)
- Trajectory of the trunk ($\theta_{t\_roll}, \theta_{t\_pitch}, \theta_{t\_yaw}$)
- Moment compensation ratio (r_{roll}, r_{pitch})

In order to realize stable dynamic walking in accordance with determined parameters, a motion is required which compensates the planned ZMP trajectory in a support polygon. In this study, the compensatory motion is realized by a horizontal motion of the waist (x_w, y_w) and a motion of the trunk ($\theta_{t\_roll}, \theta_{t\_pitch}$). Moreover, we determine a ratio to derive the compensated moment between a waist and trunk, and calculate the compensatory motions of the waist and trunk from ZMP equations based on a robot model.

Conventional robots have 6-DOF legs (2-DOF at the ankle, 1-DOF at the knee and 3-DOF at the hip joint). To derive the joint angles, the calculation of inverse kinematics is a common and effective method, which is based on the position and orientation of the foot and the waist. On the other hand, it is difficult to generate a walking pattern with the knees stretched, because the leg has a singular point at which the joint rate approaches infinity when the knee is stretched out. Therefore, based on the knee trajectories predetermined, we succeeded in a walk motion with the knees stretched.

The outline of the pattern generation is as follows:

1. The initial parameters are foot, waist, trunk, knee and ZMP trajectories. We can make various knee trajectories easily by interpolating some set points by cubic spline function that follows continuous and differential trajectories. We should plan the ZMP trajectory within the support polygon composed of contact points of the feet.
2. We can consider the legs as a 5-DOF system, because knee trajectories are predetermined. Although we consider the heights of the hip joints to be calculated dependently by the other parameters, we can reduce the difference of the heights by waist rolling motion.
3. The moments generated by the movements of the robot are computed by solving the Newton-Euler equation, which should be compensated for with a horizontal waist motion
4. We solve ZMP equation to calculate the compensatory motion of a waist and trunk in the frequency domain by FFT on the linearized biped robot model.
5. We transform the motion from the frequency domain into the time domain by IFFT. The walking pattern of the robot based on the compensatory motion is computed by solving the inverse kinematics.
6. We calculate the moment errors (eM), by substituting the compensatory motion into the strict robot model. This calculation is repeated until the error moments fall down acceptable moments (εM).

Fig. 2 shows the pattern generation using predetermined knee trajectories.

B. *Walking Pattern to Mimic a Disabled Person's Gait*

It is very important for mimicking a disabled person’s gait that as many walking parameters as possible are set according to the measured data of a subject’s gait by a motion capture system and force plates for the FRF. However, a robot might not realize a stable walking because of the difference between the subject and the robot’s model if we determine all of the walking parameters according to the measured data.

As a solution, a part of walking parameters as “setup parameters” are determined according to the measured data and we derive the compensatory motions of a waist and trunk from ZMP equations based on a robot model. Then, we can obtain a walking pattern by the calculation of inverse kinematics in the same way mentioned in sec. A. Moreover, we minimize the total of integral angle errors at all of the joints with an optimization of the other parameters as “optimized parameters”. This will help to balance “to emulate a disabled person’s gait” and “to realize a stable walking”.

Thus we have developed an algorithm that enables a biped humanoid robot to emulate gaits of disabled persons based on the ZMP criterion by using the algorithm of the pattern generation using predetermined knee trajectories mentioned above. The detail of this method is described below.

First of all, we need a classification of the walking parameters into “setup parameters” and “optimized parameters”. The trajectories of the feet, hands and ZMP characterize gaits and then are regarded as “setup parameters”. Second, the angle trajectories at the knee joints and the waist yaw joint are easy to measure with a gait analysis and we classify them as “setup parameters”. On the other hand, the angle trajectory at the waist pitch joint and the moment compensation ratio are classified as “optimized parameters” because they’re difficult to measure accurately with a gait analysis. As for the others, the horizontal motion of the waist (x_w, y_w) and the motion of the trunk ($\theta_{t\_roll}, \theta_{t\_pitch}$) are determined by deriving a ZMP equation. And the height and roll angle trajectories of the waist (z_w, θ_{w_roll}) are calculated dependently based on kinematics.

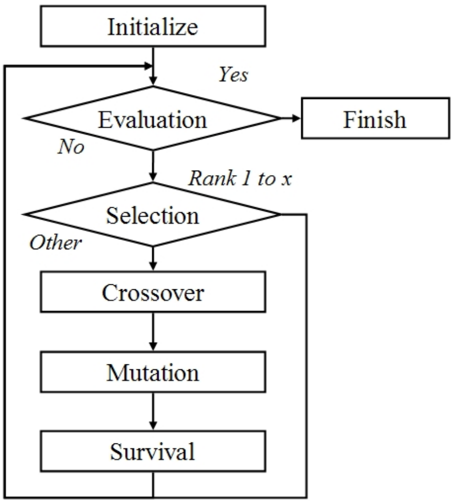


Fig. 3. Flowchart of Genetic Algorithm

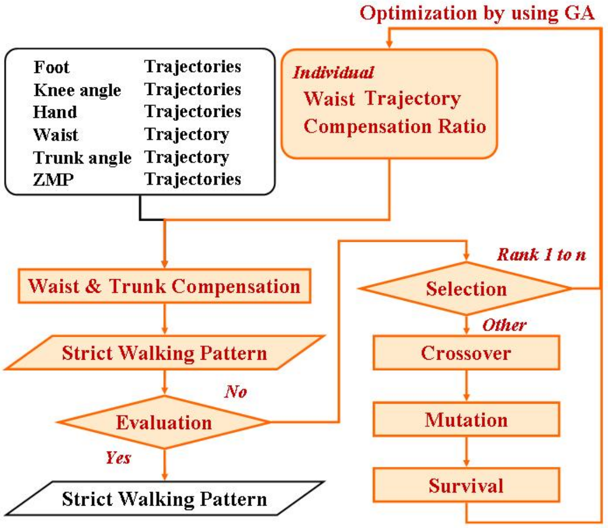


Fig. 4. Algorithm of walking pattern generation for disabled persons

Second, we set an evaluation function to minimize the total of integral angle errors at all of the joints. The evaluation function *F* used for the optimization is shown below.

$$F = \sum_{joints} \int \left| \theta_{pat} - \theta_{sub} \right| dt \qquad (1)$$

θ_{pat} : joint angles in a generated walking pattern
θ_{sub} : joint angles which are measured from a disable person’s gait

And we use Genetic algorithm (GA) for the optimization to minimize the value of the evaluation function. GA is hardly likely to be dependent on initial parameters and to converge on local solutions. In this study, we set “Initialization”, “Evaluation”, “Selection”, “Crossover” and “Mutation” in GA. And an elite choice method, roulette one and tournament one are adopted as the “Selection”. The flowchart of GA is shown in fig. 3.

The procedure of the pattern generation is described below.

1. Setup parameters are set according to the measured data of a gait. And optimized parameters are determined at random.
2. In the same way in sec. A, we calculate the compensated moment and the compensatory motions of the waist and trunk based on a ZMP equation.
3. We obtain the time-series angle trajectories of all of the joints as a walking pattern with the calculation of kinematics according to the motion and the walking parameters.
4. The walking pattern is evaluated to calculate the value of the evaluation function according to the generated pattern and the measured data.
5. We search the optimized parameters to minimize the value and obtain a proper walking pattern.

Fig. 4 shows the flowchart of the pattern generation and table 1 shows the parameters for GA.

Table 1. Parameters for GA

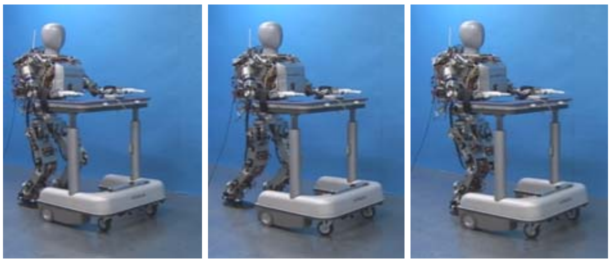
Chromosome size	3
Population size	40
Elite size	1
Probability of the crossover	0.60
Probability of the mutation	0.01

IV. EXPERIMENTS

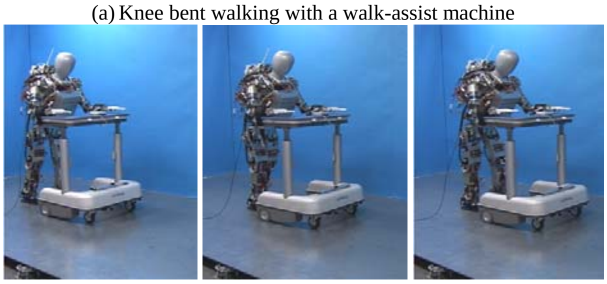
A. *Walking Experiment while moving a walk-assist machine*

The robot was programmed to move a walk-assist machine. The parameters of the experiment were: a step cycle of 0.96[s/step], a step height of 0.03[m], a step length of 0.20[m] and the three different positions of the forearms to hold the machine (0.85[m], 0.90[m], and 0.95[m]). The results showed that robot can move a walk-assist machine stably while walking. Fig. 5 shows snapshots of two different walking motions with the walk-assist machine (the height of 0.90[m]). Fig. 6 shows experimental data of the reaction forces applied to the right arm and leg, and the energy consumption on the motors at the knees in the walking with the knees bent while moving the machine.

From a clinical point of view, the position of arms is generally set according to the height of user's elbow. If a user is not handicapped, it should be set higher than the initial position. On the other hand, if he/she is handicapped, it should be placed lower. Fig. 7 shows a direct relation between the height of the forearms and the ground reaction force. Moreover, we can see that the higher the arm position is, the more energy consumption increases as shown in Fig. 7. These preliminary results demonstrate that WABIAN-2R may provide useful quantitative data.

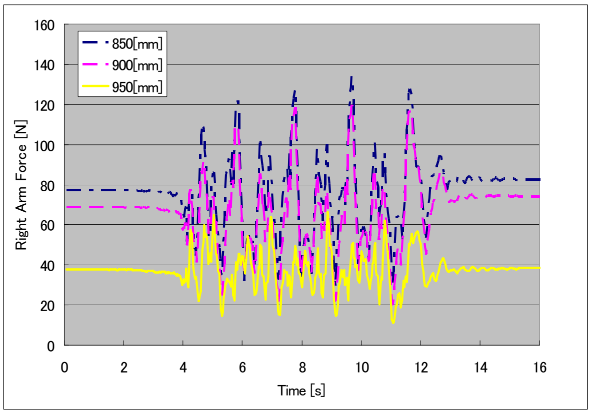


(a) Knee bent walking with a walk-assist machine

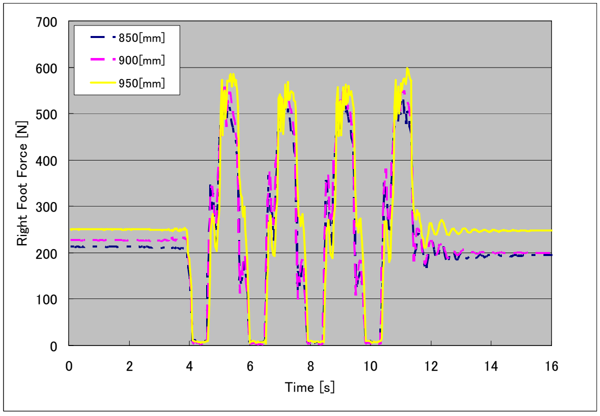


(b) Knee stretched walking with a walking assist machine

Fig. 5. Walking experiment with a walk-assist machine



(a) Right forearm



(b) Right leg

Fig. 6. Reaction forces of the forearm and the knee

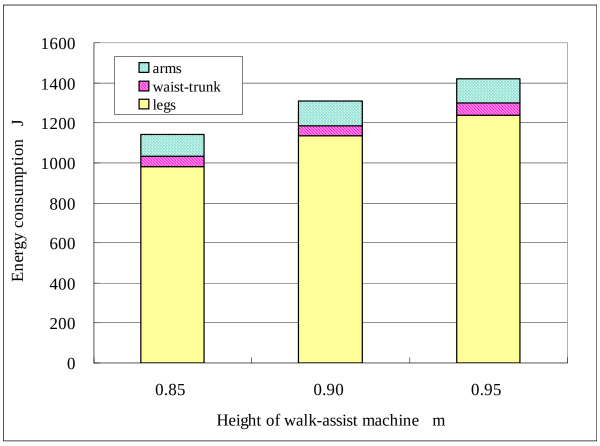


Fig. 7. Comparison of energy consumptions

B. *Emulation of the hemiplegic gait*

A walking experiment for emulation of a disabled person was carried out on a horizontal flat plane by using WABIAN-2R. The target subject for the emulation in this experiment is a 44 year old male (the body height: 1.79[m], the body weight: 98[kg]) whose disorder is a cerebral paralysis and symptom is a hemiplegic gait (the left leg is an affected limb).

In order to emulate the gait, we need to make adjustments in the walking pattern for two reasons below. One is that there are the differences of the physical properties, for example, the body length, the link proportion or the weight distribution. Therefore, we need a correction of the trajectories of the feet, hands and ZMP according to the fraction of the length between the hip

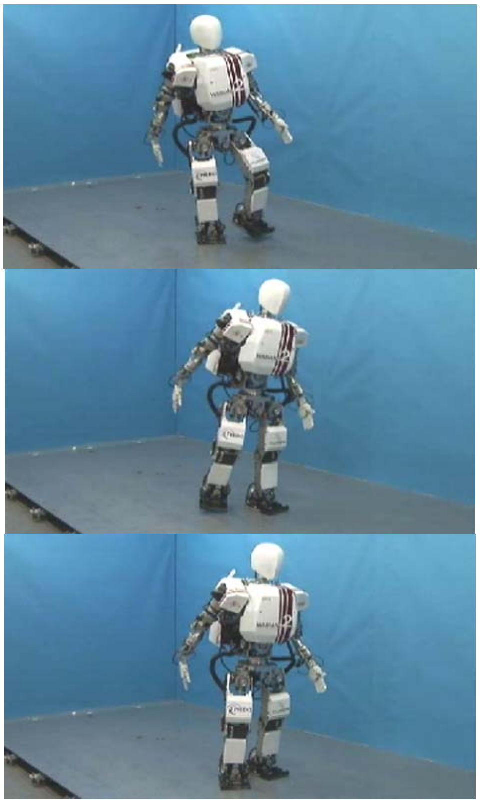


Fig. 8. Emulation of a hemiplegic gait

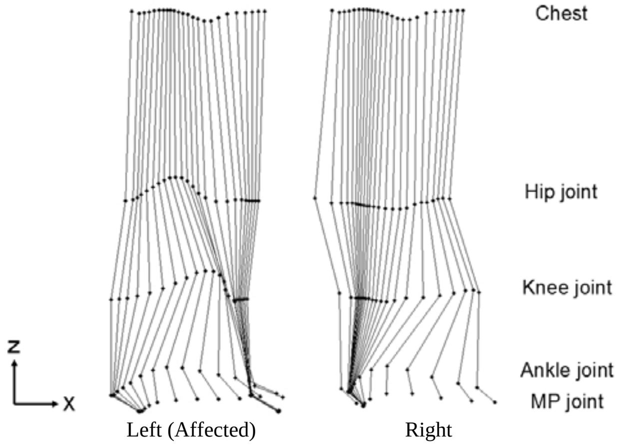
joints to emulate by WABIAN-2R. The other is that some of the joints are not able to realize a high-speed adaptive movement at the ankle joint when the foot lands because of the drive system with a high reduction ratio.

The parameters of the experiment are a step cycle of left leg (affected limb) of 1.56[s/step], right leg of 1.04 [s/step] and a step length of 0.32 [m/step]. The results showed that stable walking can be performed. Fig. 8 shows the snapshots in the walking experiment and Fig. 9 and 10 show the comparison of stick diagrams on sagittal plane and FRF between results of the subject and that of WABIAN-2R. The tendency of the gait is shown on the diagrams, although the motion of the right hip joint is not strictly emulated. The ground reaction force denoted the same tendency of that of the subject, especially the rising edge when the affected limb lands.

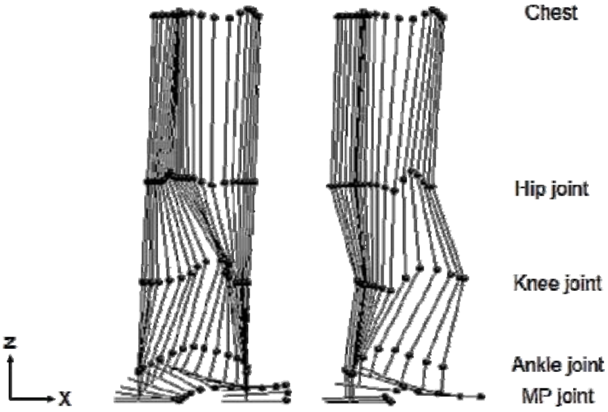
V. CONCLUSION AND FUTURE WORK

We developed the WABIAN-2R which is able to mimic human motions and the algorithm of walking pattern generation which enables a biped humanoid robot to emulate gaits of a disabled person.

Two kinds of experiments are conducted with walking while moving a walk-assist machine. In the first experiment, the robot was programmed to move a walk-assist machine while walking. As a result, the robot could provide quantitative data of the walking motion while moving the walk-assist machine. Moreover, we could find a correlation between the energy consumptions at the knee joints and the height of the forearms. On the second experiment, we succeeded in emulation of a hemiplegic gait to demonstrate the feasibility of the human motion simulator based on a comparison of stick diagrams on sagittal plane and FRF.



(a) Subject



(b) WABIAN-2R

Fig. 9. Comparison of stick diagrams between a subject and WABIAN-2R

As a feature work, we plan to do the following things:

(1) Evaluate an existing walk-assist machine by carrying out an experiment to emulate gaits of a disabled person with the walk-assist machine.

(2) Use WABIAN-2, as a simulator, not only for improving walk-assist machines but also other rehabilitation systems (i.e. an artificial legs, a gait training equipment, etc).

(3) Apply WABIAN-2 not only for medical and welfare applications but also for other fields (i.e. going up and down the stairs, sitting on and rising from a chair, dancing, etc.).

Our long-term goal is to develop a human motion model which can be applied to various research fields.

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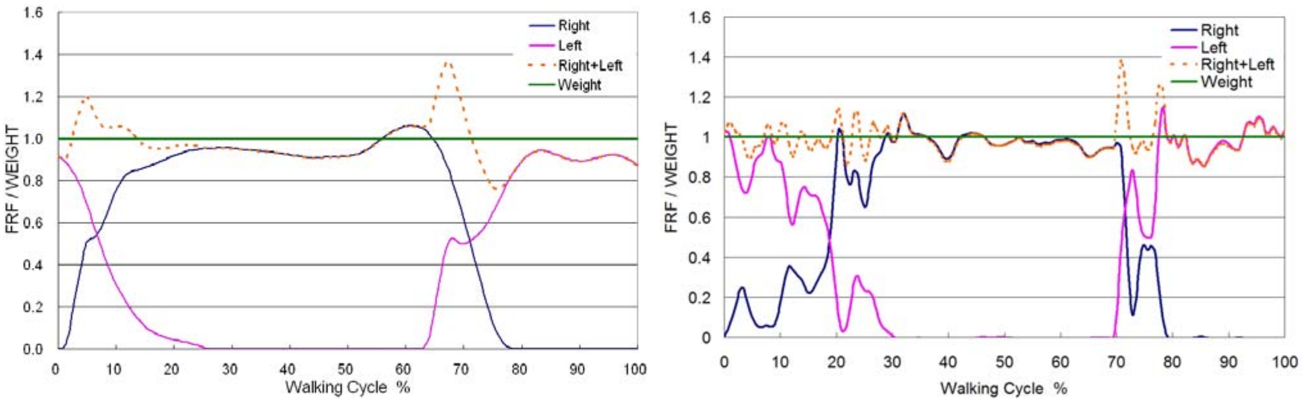

(a) Subject (b) WABIAN-2R

Fig. 10. Vertical floor reaction force

their support.

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