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Development of a Human-like Walking Robot Having Two 7-DOF Legs and a 2-DOF Waist*

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Abstract - **Almost all conventional biped humanoid robots have difficulties in realizing various walking motions such as knee stretch walking like a human because of an insufficiency of DOF. Therefore, we have developed a 16-DOF biped humanoid robot without a trunk: 3-DOF in each ankle, 1-DOF in each knee, 3-DOF in each hip and 2-DOF in the waist. Using the biped robot, basic experiments are conducted and the effectiveness of the leg mechanism is confirmed.**

Index Terms* - *Biped Humanoid Robot, New Leg Mechanism, Various Walking Motions, Stretch Walking

I. Introduction

Recently biped humanoid robots have been expected to cooperate with humans in various fields for reasons of isomorphism of humanoid, affinity and adaptability to human environment and so on. So many researchers have been studying on their mechanisms and control.

The humanoid group in Waseda University has been studying about biped humanoid robots since 1966. The first biped humanoid robot WABOT-1 was developed in 1973 and realized the static walking on a horizontal plane. Moreover, we realized the dynamic complete walking on even or uneven terrain using WL series [2]. The dynamic biped walking was achieved under the unknown external forces applied by an environment [3]. Also, the emotional motion of the biped robot was presented which is expressed by the parameterization of its body motion [4]. In 2002, an online pattern generation was developed [5]. By using this method, various walking experiments with visual and auditory information were carried out [6]. Also, a research group of HONDA has developed the humanoid robot P2, P3, and ASIMO [6] [7]. ASIMO can walk continuously while changing direction and can go up/down stairs without its balance. Japanese National Institute of Advanced Industrial Science and Technology and Kawada Industries, Inc. have developed HRP-2 [8] and HRP-2P [9].

However, it is difficult to say that the above mentioned biped humanoid robots are equal to humans in physical motion. Especially these conventional biped robots cannot realize knee stretch walking. The main reason why they usually walk with knees bent is a singularity problem: walking patterns of many biped robots are calculated by solving six dimensional inverse kinematics, based on the position and orientation of the foot and the waist. It is difficult for this method to create a stretch walking pattern because the leg has the singular point at which the joint rate approaches infinity when the knee is stretched out. Actually humans have more number of redundant DOF than conventional biped humanoid robots, which makes it possible for them to achieve various motions by using many DOF effectively. Therefore we decided to develop a new biped robot WABIAN-2 which has more human-like DOF configuration than current robots have.

In advance of this study, we already have proposed and developed an algorithm which enables a biped humanoid robot to stretch its knees in steady walking avoiding singularity by using waist motion [10]. In this paper, we describe a new biped walking leg named WABIAN-2 LL (WAseda Bipedal humanoid-2 Lower Limb), which has two seven DOF legs and a two DOF waist. Also we describe basic walking experiment to confirm our mechanical and system design of WABIAN-2 LL and the stretch pattern generation method.

II. Configuration of DOF

A. 2-DOF Waist

Human's waist motion in steady walking is observed in frontal plane (defined as roll motion in this study) and horizontal plane (defined as yaw motion) as shown Fig. 1. Waist motion in sagittal plane (defined as pitch motion) is seldom observed in a stick diagram as shown Fig. 2. These show that a humanoid should be able to roll its waist and to yaw it independently of its trunk posture.

Also a study of gait analysis and bio mechanics reported that the following pelvis motion: two hipbones are combined by a cartilage, which is named pubic symphysis. In steady walking, it moves like a crank joint. According to this motion, two hipbones are sliding on each other. So we think the hip joint is able to make two dimensional circular motions as shown in Fig.3. If a biped walking robot has the joints of the waist, human-like walking will be realized such as a stretch walking, a zigzag walking and so on by using waist motion as redundancy.

The roll axis and yaw axis should be at right angles to each

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other in the middle of the two hip joints because the displacement of the trunk by waist motion will be the smallest and the kinematics also will be simplified most. So, we propose a two DOF waist system of a humanoid robot that can move like human waist.

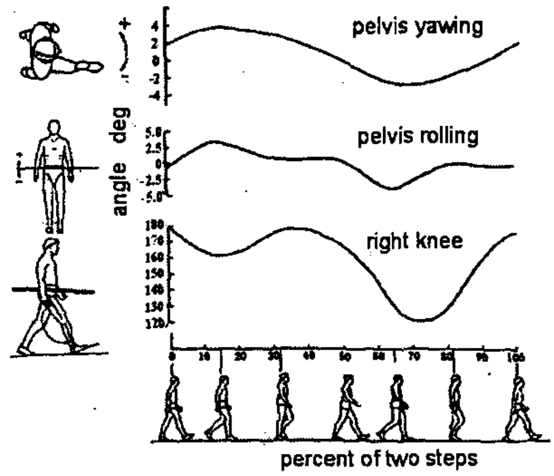

Figure 1. Human's pelvis and knee motion [10]

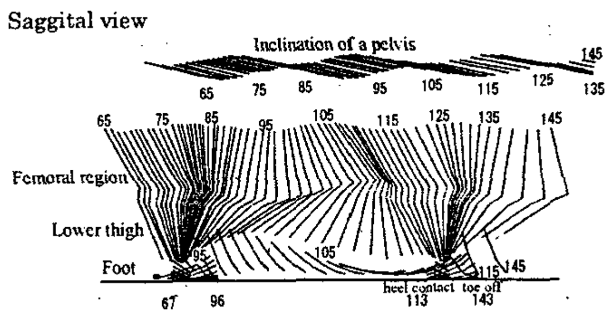

Figure 2. Stick diagram of human leg motion [10]

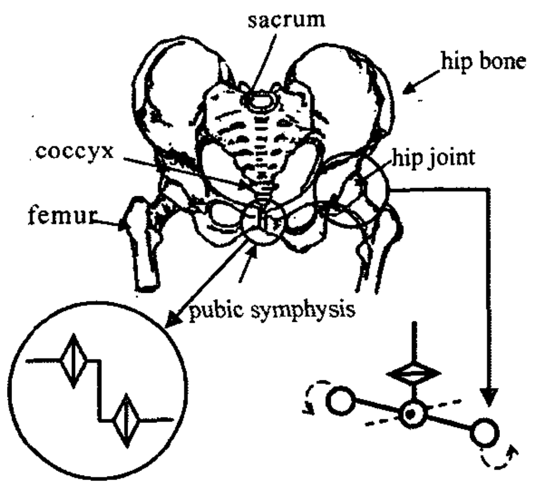

Figure 3. Pelvis of a human

B. 7-DOF Legs

The ankles of almost all conventional biped humanoid robots consist of the pitch and the roll axes as shown in Fig. 4(a). It is difficult for the biped walking robot to balance its body in various environments. If the ankle is composed of pitch, roll and yaw joint, the biped robot can select a stable position and reduce the impact and/or contact forces produced between the landing foot and the ground using a proper control algorithm. In this research, we have developed a new biped walking system that has two 3-DOF ankles, two 1-DOF knees, two 3-DOF hips and a 2-DOF waist as shown in Fig. 4(b).

Moreover this leg system has an advantage in generating diverse walking patterns by using the leg redundancy. Biped robots which have only 6-DOF legs allow a unique knee orientation when position and orientation of those foot and waist are set. On the other hand, a biped robot which has 7-DOF legs proposed in this study can rotate knee orientation independently of foot trajectory. Therefore, this leg system will be useful when avoiding obstacles: for example, climbing a ladder up and down, riding on something, working in a narrow place and so on (Fig. 5).

III. Mechanisms

A. Overview of design

WABIAN-2 LL has been designed to become a humanoid which has whole body with the height of 1.5m and the weight of 50kg. In this study, this leg module which consists of two legs, a waist, a trunk, and two ballasts has the height of 1.228m and the weight of 40kg. It also is very important for a humanoid to be designed in view of light weight, high stiffness and wide movable range. So we mainly selected duralumin as the structural member in order to realize those antithetical concepts. Fig. 6 and 7 show the dimensional drawing and photo of WABIAN-2 LL. Also Fig. 8 shows the leg part drawn by 3D-CAD.

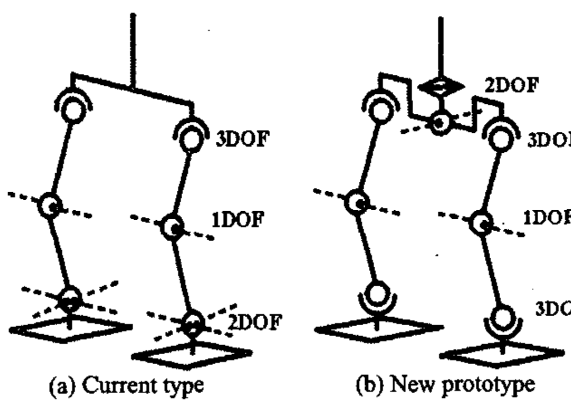

Figure 4. Configurations of DOF

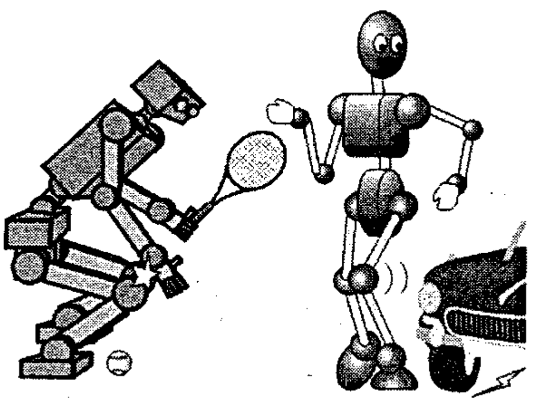

Figure 5. Advantages of 7-DOF legs

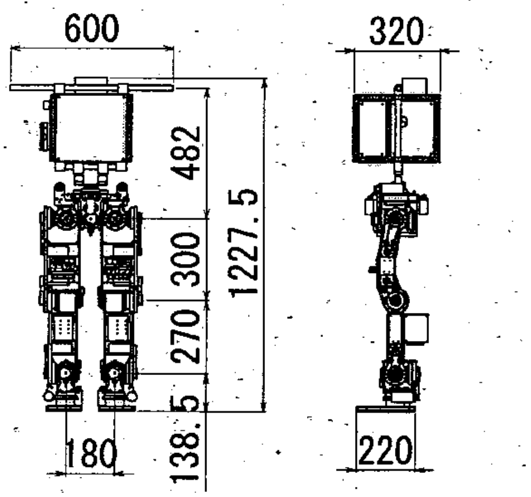

Figure 6. Assembly of WABIAN-2 LL

B. *Joint specification*

Specifications of each joint such as maximum torque and rotating speed are designed based on the results of the software simulation by using Newton-Euler's Method and estimated mass distribution. The simulation is carried out to realize fast walking with walking speed of 0.48s/step and step length of 0.3m/step.

Each actuator system of joint consists of a motor, a Harmonic drive gear, a lug belt and two pulleys. This double speed reduction mechanism not only allows high reduction ratio but also a joint axis to be set apart from a motor axis. Therefore we could design a human-like leg mechanism without a big projection. DC motors were selected as actuators in consideration of torque/weight ratio. Table 1 shows specification of joints in detail.

IV. CONTROL SYSTEM

WABIAN-2 LL is controlled by a PC which is mounted on its trunk, without any support from outside except for power supply. A Titech Robot Driver Ver. 1 is equipped on its body for a servo driving. Each actuator system is equipped with an incremental encoder attached to the motor shaft, and a photo micro sensor attached to the joint shaft in order to detect an initial posture. Also each ankle is equipped with a six axes force/torque sensor which is used for measuring floor reaction force and ZMP.

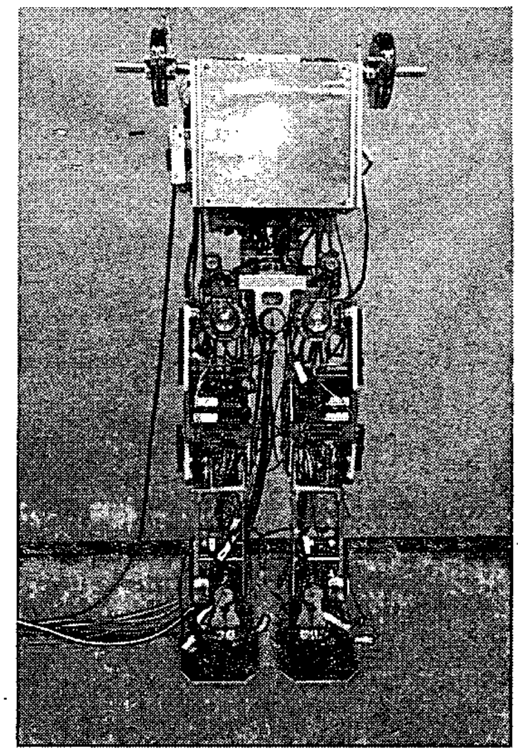

Figure 7. Photo of WABIAN-2 LL

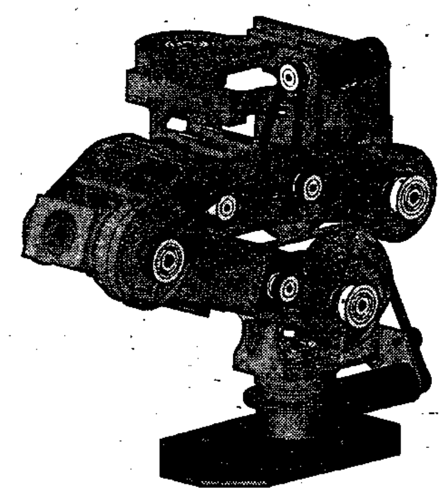

Figure 8. Leg part of WABIAN-2 LL

Table 1 Specifications of WABIAN-2 LL

	Ankle yaw	Ankle roll	Ankle pitch	Knee pitch	Hip pitch	Hip roll	Hip yaw	Waist roll	Waist yaw
Max torque[Nm]	23.5	70.4	55.8	150.9	55.8	70.4	23.5	70.4	23.5
Max angler velocity[deg/sec]	361	305	386	314	386	305	361	305	361
Rated output[W]	22	90	90	150	90	90	22	90	22
Reduction ratio	300	229	181	365	181	229	300	229	300
Movable range of humans[deg]	-10	-20	-25	0	-15	-20	-45	-5	-5
	20	30	45	130	125	45	45	5	5
Movable range of WABIAN-2 LL [deg]	-90	-40	-33	0	-35	-22	-100	-20	-90
	90	25	118	-160	104	22	20	15	90

The control PC consists of a PCI CPU board with Pentium III (1.26GHz), which is connected to I/O boards through PCI bus. I/O boards are a Ritech Interface board which has 16ch D/As, 16ch Counters and 12ch PIO, and a six axes sensor receiver board. Fig. 9 shows the control system. As a real time operating system, QNX Realtime Platform was selected.

V. WALKING EXPERIMENTS

A. *Normal walking*

Normal walking experiments which means previous walking with a constant waist height and bending knees at all times were carried out on a horizontal flat plane by using WABIAN-2 LL. The experiments were done with a step cycle of 0.96s/step, a waist height of 0.63m, a step height of 0.04m and five different step lengths of every 0.05m from 0.00m to 0.20m.

The results showed that stable walking with step lengths of up to 0.15m can be realized. However in the case of step length of 0.20m, the walking showed unstable action which was considered to be caused by the moment generated about yaw axis. Therefore a walking pattern with compensatory yaw motion using the waist yaw joint was generated by a pattern generation algorithm and a walking experiment with yaw motion was carried out. As a result, stable walking with the step length of 0.20m was realized. From the result, we see that the compensatory yaw motion is very important in increasing step length. Fig. 10 shows a scene of the walking experiment with yaw motion. Fig. 11 shows the right knee patterns calculated by a pattern generator (reference) and measured by the motor encoder (response). Also Fig. 12 shows the designed Y-ZMP trajectory (reference) and the Y-ZMP trajectory measured by the six axes force/torque sensors in this experiment (response).

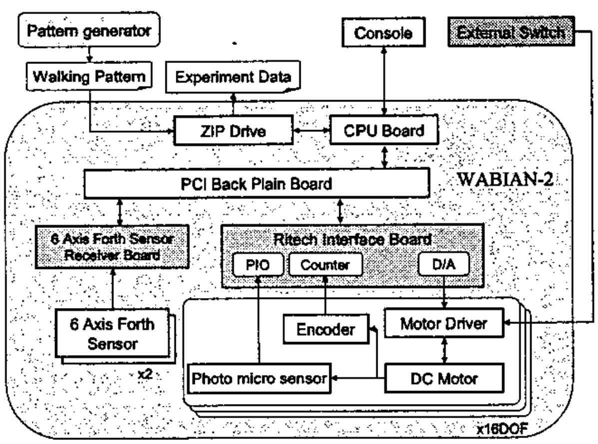

Figure 9. Control system of WABIAN-2 LL

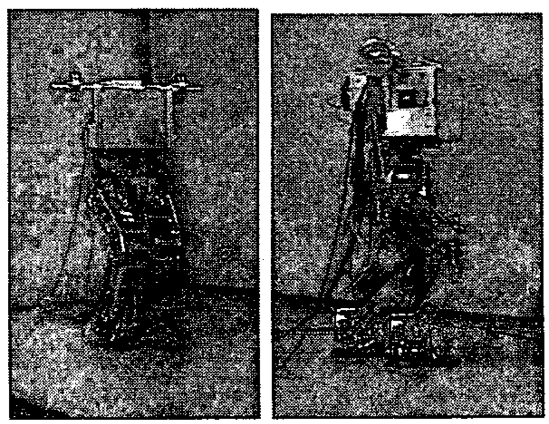

Figure 10. Normal walking experiment

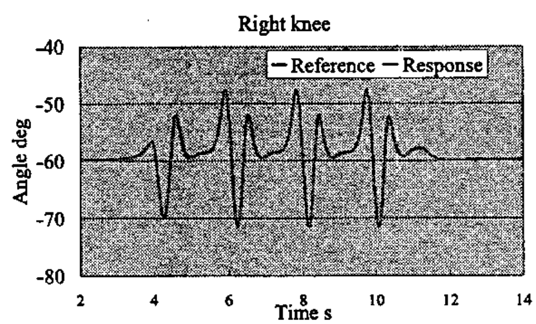

Figure 11. Normal walking ZMP trajectory

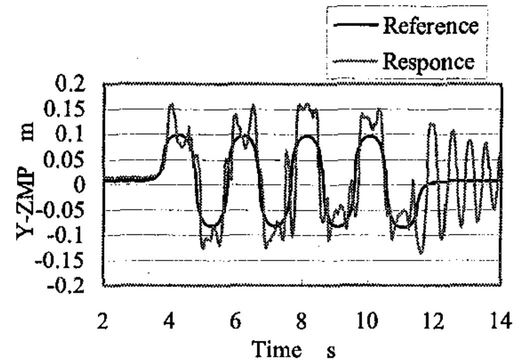

Figure 12. Normal walking ZMP trajectory

B. *Stretch walking*

Stretch walking experiments were carried out on a horizontal flat plane by using WABIAN-2 LL and generated stretch walking patterns. Essential features of the pattern generation are listed below.

- Calculation of a joint angle differs depending on whether the leg is in swinging phase or supporting phase.
- Knee angle of supporting leg is set as an initial parameter.
- Knee stretching is determined by angular velocity limitation.
- The singularity of the swinging leg can be avoided using waist roll motion.

More details about the stretch walking pattern generation are reported [9].

The experiments were done with a step cycle of 0.96s/step, a step height of 0.04m and five different step lengths of every 0.05m from 0.00m to 0.20m. A knee joint pattern of supporting leg $\theta(t)$ deg was set as (1)

$$\theta(t) = -10\left(1+\sin\left(\frac{2\pi}{T}t\right)\right) \tag{1}$$

where T is supporting phase time. T was set as 0.96s in this experiment.

The results showed that stable walking with all step lengths can be realized. Fig. 13 shows a scene of the walking experiment with a step length of 0.2m/step. Fig. 14 shows the right knee patterns calculated by a pattern generator and measured by the motor encoder. Also Fig. 15 shows the designed Y-ZMP trajectory and the Y-ZMP trajectory measured by the six axes force/torque sensors in this experiment.

C. *Knee turning*

Knee turning experiments were conducted for the purpose of confirming the effectiveness of the mechanical design of WABIAN-2 LL. The experiments were done while the robot stood on two legs on a horizontal flat plane, with a waist height of 0.63m and three different maximum knee turning angle of 40deg, 70deg, and 90deg. A knee turning angle pattern $\phi(t)$ deg was set as (2)

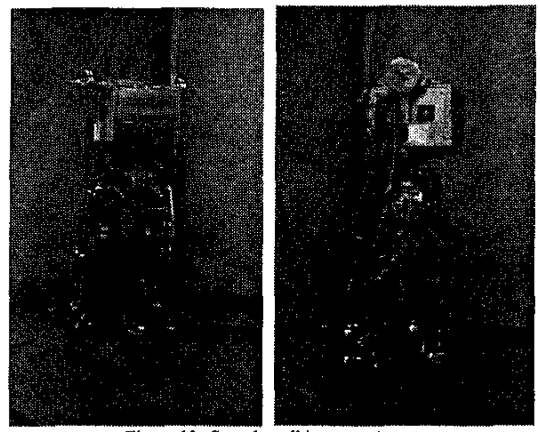

Figure 13. Stretch walking experiment

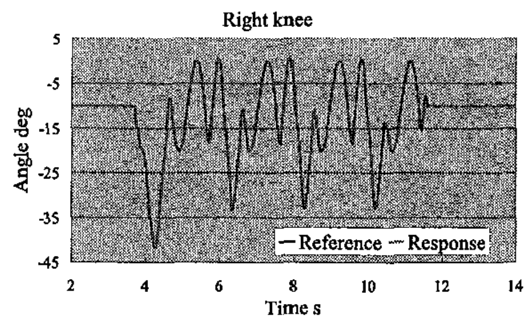

Figure 14. Normal walking ZMP trajectory

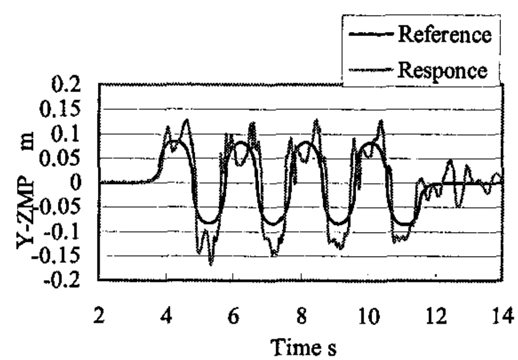

Figure 15. Stretch walking ZMP trajectory

$$\phi(t) = \frac{\phi_{\max}}{2}\left(1 - \cos\left(\frac{2\pi}{T}t\right)\right) \qquad (2)$$

where T is knee turning cycle. T was set as 0.96s in this experiment.

The results showed that knee turning by the biped robot could be realized with all maximum knee turning angles. Fig. 16 shows a scene of the experiment with the maximum knee turning angle of 90 deg.

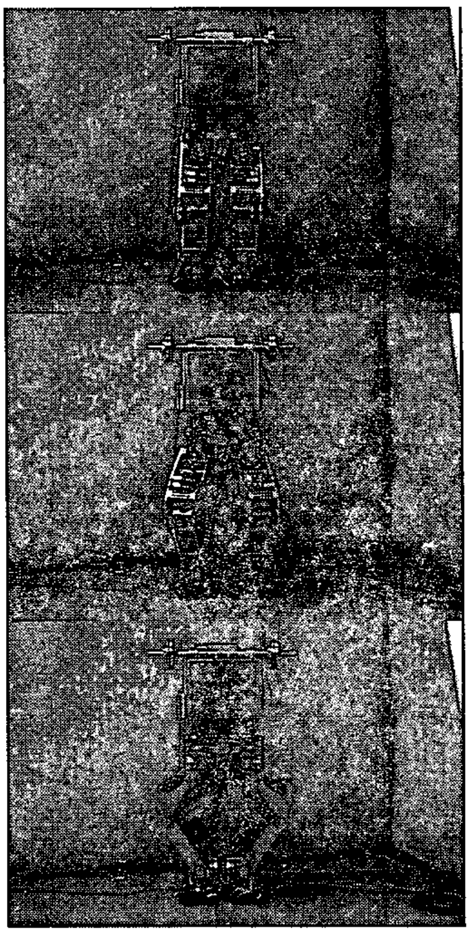

Figure 16. Knee turning experiment

VI. Conclusion and Future Work

We developed a new biped leg module that has two 3 DOF ankles, two 1 DOF knees, two 3 DOF hips and a 2 DOF waist. Through walking experiments, the effectiveness of this basic mechanical and control system and the pattern generation methods [9] were confirmed.

However the biped robot could not realize any stable walking with a step length of more than 0.2m/step because of the mechanical displacement between a generated pattern and a real motion caused by low stiffness of the framework and the servo driving. In the near future, we will make improvements in stiffness of the robot and in the pattern generation method to realize more human-like walking and longer step length walking.

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References

[1] J. Yamaguchi, E. Soga, S. Inoue, A. Takanishi, "Development of a Bipedal Humanoid Robot -Control Method of Whole Body Cooperative Dynamic Biped Walking-," Proc. IEEE Int. Conference on Robotics and Automation, pp. 368-374, 1999.

[2] H. Lim, Y. Yamamoto, A. Takanishi," Stabilization Walking Control for Human-like Biped Robots," Advanced Robotics vol.16 No.4 pp361-380

[3] H. Lim,Y. Kaneshima, A.Takanishi, "Online Walking Pattern Generation for Biped Humanoid with Trunk," Proc. IEEE Int. Conference on Robotics and Automation, pp. 3111-3116, 2002.

[4] Y. Ogura, Y. Sugahara, Y. Kaneshima, N. Hieda, H.O. Lim and A. Takanishi, "Interactive Biped Locomotion Based on Visual/Auditory Information," Proc. IEEE Int. Workshop on Robot and Human Interactive Communication, pp. 253-258, 2002.

[5] K. Hirai, M. Hirose, Y. Haikawa, and T. Takenaka, "The Development of Honda Humanoid Robot," Proc. IEEE Int. Conference on Robotics and Automation, pp. 1321-1326, 1998.

[6] Y. Sakagami, R. Watanabe, C. Aoyama, S. Matsunaga, N. Higaki and K. Fujimura, "The intelligent ASIMO: System overview and integration," Proc. IEEE/RSJ Int. Conference on Intelligent Robots and Systems, pp. 2478-2483, 2002.

[7] K. Kaneko, F. Kanehiro, S. Kajita, K. Yokoyama, K. Akachi, T. Kawasaki, S, Ota, and T. Isozumi, "Design of Prototype Humanoid Robotics Platform for HRP," Proc. IEEE/RSJ Int. Conference on Intelligent Robots and Systems, pp. 2431-2436, 2002.

[8] K. Fujiwara, F. Kanehiro, S. Kajita, K. Yokoi, H. Saito, K. Harada, K. Kaneko, H. Hirukawa," The First Human-size Humanoid that can Fall Over Safely and Stand-up Again," Proc. IEEE/RSJ Int. Conference on Intelligent Robots and Systems, pp. 1920-1926, 2003.

[9] Y. Ogura, H. Lim, A. Takanishi, "Stretch Walking Pattern Generation for a Biped Humanoid Robot," Proc. IEEE/RSJ Int. Conference on Intelligent Robots and Systems, pp. 352-357, 2003.

[10] P. E. Klopsteg and P. D. Wilson, et. al., "Human Limbs and Their Substitutes," New York Hafner, 1963.