Development of a New Humanoid Robot WABIAN-2[*]

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Abstract - **A new humanoid robot—WABIAN-2— that can be used as a human motion simulator is proposed in this paper. Its trunk is designed in order to permit rotation, and forward, backward, and sideway movement. Further, its arms are designed to support its complete weight when pushing a walk-assist machine. Moreover, it can lean on a walk-assist machine by forearm control using trunk motion. Basic walking experiments with WABIAN-2 are conducted with and without a walk-assist machine, thereby confirming its effectiveness.**

Index Terms - Robot Design, Humanoid Robot, Biped robot, Various Walking Motions, Stretch Walking

I. INTRODUCTION

With the rapid aging of society in recent times, the number of people with limb disabilities is increasing. According to a research by the Health, Labour and Welfare Ministry, a Japanese government agency, there are around 1,749,000 people with limb disabilities; this accounts for more than half of the total number of disabled people (3,245,000 handicapped people). The majority of these people suffer from lower-limb disabilities. Therefore, the demands for establishing a human walking model that can be adapted to clinical medical treatment are increasing. Moreover, this model is required for facilitating the development of rehabilitation and medical welfare instruments such as walking machines for assistance or training (Fig. 1(a)). However, experiments to estimate the effectiveness of such machines by the elderly or handicapped could result in serious bodily injury.

Many research groups have been studying biped humanoid robots in order to realize robots that can coexist with humans and perform a variety of tasks. For example, a research group from HONDA has developed 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 developed H6 and H7 [4][5], and the Technical University of Munich developed Johnnie

[6]. Waseda University developed the WABIAN series that realized humanoid walking with a 3-DOF trunk motion and a 3-axis zero moment point (ZMP) compensation using the trunk [7][8]. Korea Advanced Institute of Science and Technology (KAIST) also developed a 41-DOF humanoid robot— KHR-2 [9].

The above mentioned human-size biped robots achieved stable and dynamic walking. If these humanoid robots can use rehabilitation or welfare instruments as shown in Fig. 1(b), they could help in testing such instruments quantitatively. The main advantages of the simulator can be considered to be as follows: (1) The measurement of the angle and the torque required at each joint can be measured easily and quantitatively as compared to the corresponding values in the case of a human measurement. (2) Experiments using such robots can help identify leg defects of a human from an engineering point of view. (3) A robot can replace humans as experimental subjects in various dangerous situations: experiments involving the possibility of falling, tests with incomplete prototype instruments, simulations of paralytic walks with temporarily locked joints.

Such experiments require a humanoid robot with mechanisms and a control system that enables it to closely replicate a human. However, humans have more redundant DOFs than conventional biped humanoid robots; this feature enables them to achieve various motions. Therefore, the assumption of a DOF configuration that is necessary to reproduce such motions is one of the very important issues in the development of a humanoid robot.
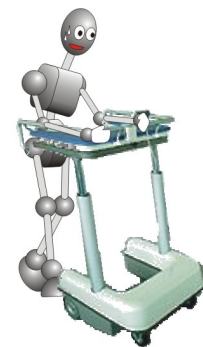
(a) by human   (b) by robot
Figure 1.   Walk-assist machine

In this paper, a new humanoid robot—WABIAN-2—with two 7-DOF legs, a 2-DOF waist, a 2-DOF trunk, and two 7-DOF arms is proposed. First, a DOF configuration based on researches from the viewpoint of clinical medicine is described. Next, the mechanisms and control system of the robot are presented. In the development of the robot, a new design principle for a robot that is capable of using a walk-assist machine is set as the primary objective of this study. The effectiveness of this developed humanoid robot is confirmed by walking experiments.

II. DESIGN CONCEPT

A. Discussion of human motion

Human body mechanism basically comprises bones as rigid links, cartilages as joints, muscles and tendons that actuate each part of the body. It is impossible to replace all of this muscular-skeletal system by current mechanical components. Therefore, the primary goal of the mechanical design should be considered as development of a robot that can imitate equivalent human motion.

Klopsteg et al. have proposed the result of the gate analysis of humans [10]. Figure 2 shows the pelvis and the knee motion plotted in the steady walking phase. The data is based on experimental results of 8 people walking motion who do not have physical handicaps. In the result, human's pelvis motion in steady walking is observed in frontal plane (defined as roll motion in this study) and horizontal plane (defined as yaw motion). Waist motion in side plane (defined as pitch motion) is seldom observed. According to this a humanoid robot which can perform walks similar to human should be able to move its hips in roll and yaw axes. These hip movements have to be independent in its trunk position.

On the other hand, Humans can move their trunk independent of the pelvic motion. The Japanese Association of Rehabilitation Medicine (JARM) and the Japanese Orthopaedic Association (JOA) have established the basic rules of representation and measurement methods for the range of motion (ROM) [11]. The general concept of ROM does not always imply joints or articulation. However, it serves as a useful guide in the development of a humanoid
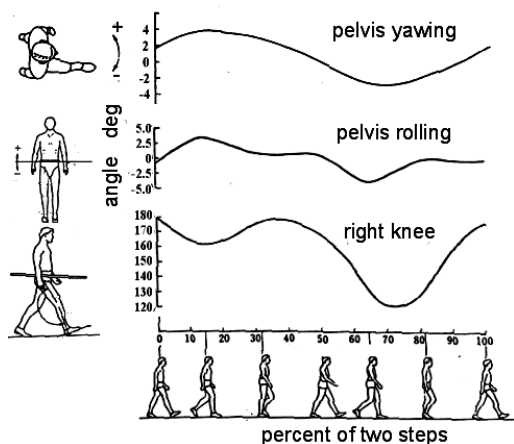
robot. Table 1 lists the rules and results for trunk motions (thoracic and lumbar spines). These ROM measurements for an average human were either carried out in a sitting position or with instruments that held the pelvis in initial position. This table shows that humans are capable of three dimensional motions at least in their trunk.

These trunk motions are essential for a human motion simulator to mimic various human motions. For example, humans bend their trunks in order to rise from a sitting position, walk with a limp swinging their trunk to maintain the balance of the entire body, or twist their trunks to walk fast. Moreover trunk motions are considered to be absorption mechanisms for positional error when the robot grasps or leans against something. When the robot leans against a rail or uses a walker or a walk-assist machine, the system composed of the robot and the instrument becomes a statically indeterminate structure. Such a system will require some redundant DOFs and a robust control method. It is considered that humans usually move their trunks subconsciously in the abovementioned cases.

B. DOF configuration

Figure 3 presents the DOF configuration of the new humanoid robot—WABIAN-2. In this study, the initial position of the robot is set as 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. 3.

Wabian-2 has two 7-DOF legs, a 2-DOF waist, a 2-DOF trunk, two 7-DOF arms, a 3-DOF neck, and two 3-DOF hands. In a 2-DOF waist system, the roll axis and yaw axis should be perpendicular to each other, and should cross the middle point between the two hip joints. This will minimize the displacement of the trunk by the waist motion and simplify the kinematics calculation. In addition, the roll joint should be

Figure 2. Human's pelvis and knee motion

Table 1 ROM of thoracic and lumber spines

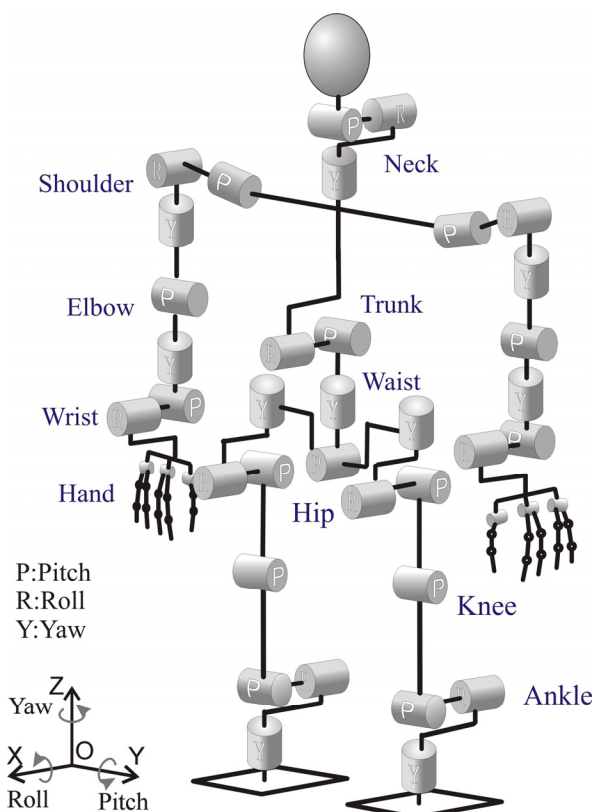| Direction of movement		ROM	figure
Flexion		45	
Extension		30	
Rotation	Left	40	
	Right	40	
Lateral bending	Left	50	
	Right	50	

Figure 3.   DOF configuration

Figure 4. Photo of WABIAN-2

positioned on the lower limb side while the yaw joint on the trunk side. This enables the yaw joint to be used as the yaw rotation for both the hips and the trunk. This DOF configuration of the waist and trunk enables substantial 3-DOF trunk motions as listed in Table 1.

III. MECHANISMS

A.   Overview

The frameworks of WABIAN-2 are mainly fabricated from aluminium alloy (5052, 2017A, 2024, and 7075) in order to realize antithetical concepts such as light weight, high stiffness, and a wide movable range. Each actuator system of the joint consists of 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 a joint axis to be set apart from the motor axis. This mechanism provides designs for a human-like joint mechanism without a considerable projection. In this paper, we mainly focus on the development of the waist, trunk, and arms. Figure 4 is a photograph of WABIAN-2. The height of the robot is 1.53 m and the weight is 64.5 kg with batteries. The specifications of each joint such as maximum torque and rotating speed are designed based on the results of software simulations. These results were computed using Newton-Euler's method and estimated using mass distribution. Several types of simulations were carried out in order to determine the joint specification. The details are described as follows:

B.   Waist and Trunk

Figure 5 and 6 show the 2-DOF waist and 2-DOF trunk system. A 2-DOF waist combination of a roll and a yaw joint is attached in the middle between the hip joints. A 2-DOF trunk having a pitch and a roll joint is assembled over the waist.

Static models and dynamic models were used in the design of the trunk joint. The static simulations are used under the assumption that the robot stands and bends its trunk forward at an angle of 45 degrees or bends sideways at 30 degrees. These ranges correspond to the maximum moveable ranges in a human, as shown in Table 1. The dynamic simulations correspond to the assumption that the robot can walk and maintain its balance by using trunk motions to compensate for the ZMP. Table 2 lists the specifications of the waist and trunk joints.

C.   Arms

The arm of WABIAN-2 has 7-DOF. Figure 7 shows the 3D-CAD. The arms were designed based on a concept that the arms of the robot can hold the robot's weight while it leans on a walk-assist machine. Since the robot can lean on a walk-assist machine, most of its weight will be distributed on both its forearms. In order to determine the suitable actuators of the arms, a software simulation was conducted. In this simulation, the robot leans on a walk- assist machine using its forearms; further, the elbow angle is separated by 15 degrees from a posture bent at a right angle when the arm supports half the
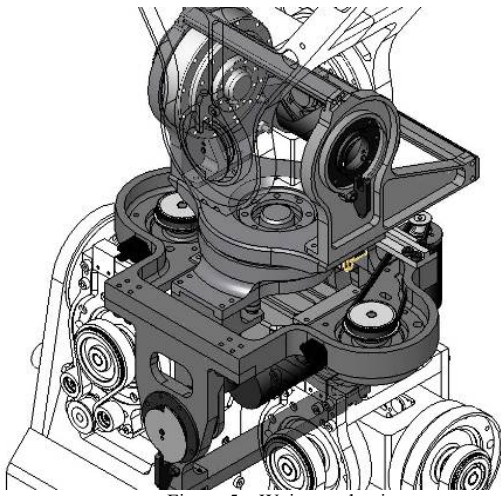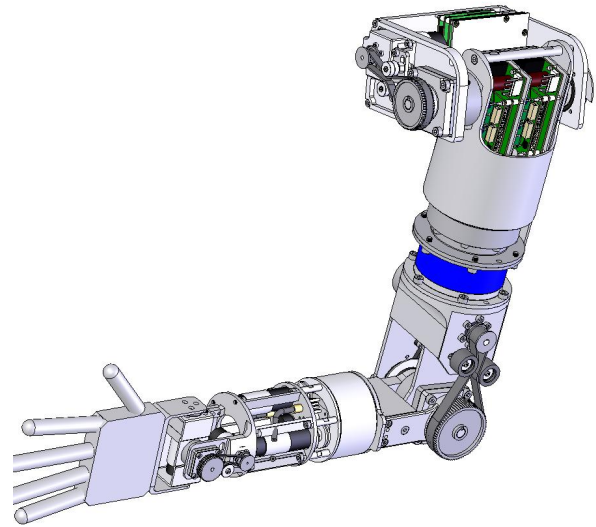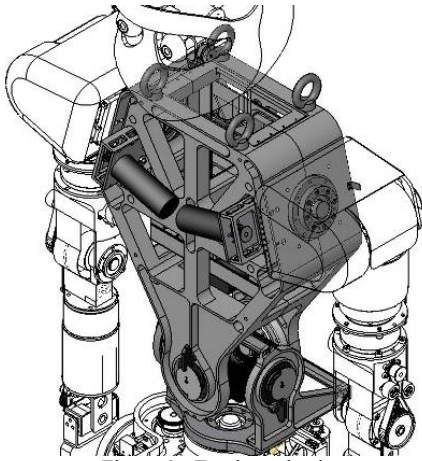
Figure 5   Waist mechanism

Figure 6   Trunk mechanism

Table. 2 The specifications of the waist and trunk joints

	Waist		Trunk	
	Roll	Yaw	Pitch	Roll
Maximum torque[Nm]	70,4	23,5	103	103
Assigned motor power rating[W]	90	22	150	150
Reduction ratio	100	300	483	483
Movable range of a human [deg]	--	--	-30	-50
	--	--	45	50
Movable range of WABIAN-2 [deg]	-16	-180	-30	-50
	16	180	45	50

weight (30 kg) of the robot (the two arms equally support the entire weight (60 kg) of the robot). Table 3 presents the specification of the joints for each arm.

Moreover, a 6-axis force/torque sensor is mounted on each upper arm. In general, a force/torque sensor is mounted on the wrist of a robot in order to enable it to grasp, push or pull something using a hand as an end effecter. However, one of the design concepts of the WABIAN-2 is a robot that can lean

Figure 7   Left arm mechanism

Table 3 Specifications of arm joints

	Wrist		Elbow		Shoulder		
	Roll	Pitch	Yaw	Pitch	Yaw	Roll	Pitch
Maximum torque[Nm]	0.40	0.40	0.40	20	2.5	7.9	20
Assigned power rating[W]	4.5	4.5	4.5	60	22	22	60
Reduction ratio	100	244	100	327	101	333	330
Movable range (Human)[deg]	-85	-15	-85	0	-80	-30	-50
	85	55	90	145	110	180	180
Movable range (WABIAN-2)[deg]	-115	-47	-180	-10	-180	-17	-180
	41	47	180	130	180	196	180

against a walk- assist machine. Therefore, the sensor must be capable of measuring external forces on the forearm.

IV. CONTROL SYSTEM

The DC motor is driven by the TD12770-48W10 or TD12770-48W05—motor drivers developed by TOKUSYU DENSO Co., Ltd. [12]. Both of them enable speed control using an electrical governor without a tacho generator, with a 100 kHz PWM. The maximum output current range of TD12770-48W10 and TD12770-48W05 are greater than 30 A at 48 V, 15 A at 48 V, respectively. The current monitor port mounted on the motor drivers is utilized in energy consumption experiments. Figures 8 and 9 present the photographs of the motor drivers. Further, a photo micro sensor is attached to each joint shaft in order to determine the initial position.

WABIAN-2 is controlled by a PC mounted on its trunk, which consists of a PCI CPU board with a Pentium M (1.26 GHz) processor, PCI backplane board, three HRP Interface board, and a six-axis sensor receiver board. The HRP Interface board has a 16 channel D/As, 16 channel counters, and a 16 channel PIO. The QNX Realtime Platform was selected as the real time operating system. Each ankle is
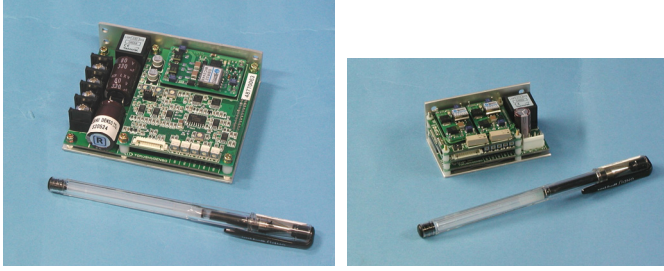
Figure 8   TD12770-48W10   Figure 9   TD12770-48W10

equipped with a six-axis force/torque sensor for measuring the floor reaction force and the ZMP. Also, each upper arm is equipped with sensor for measuring the effect of upper body in order to be used in walking with assist machine Figure 10 shows the control system.

V. EXPERIMENTS

A. Walking Experiments

In order to verify the effectiveness of the control method for forearms and hardware of the humanoid robot, walking experiments with two walking styles were carried out on a horizontal flat plane: (1) ***Conventional walking*** style with a constant waist height and bending knees at all times, (2) ***Stretch walking*** style with human like knee joint pattern including stretch out knee phases, generated a stretch walking pattern generation [13] [14].

The experiments were done with a step cycle of 0.96s/step, a step height of 0.03m and five different step lengths from 0.00m to 0.20m with 0.05m difference. The results showed that stable walking with all step lengths can be performed. Figure 11 and 12 show pictures of the walking experiment with a step length of 0.20m/step.

B. Walking with a walking assist machine

In order to verify the concept of the humanoid robot as a human motion simulator, assisted- walking experiments with a
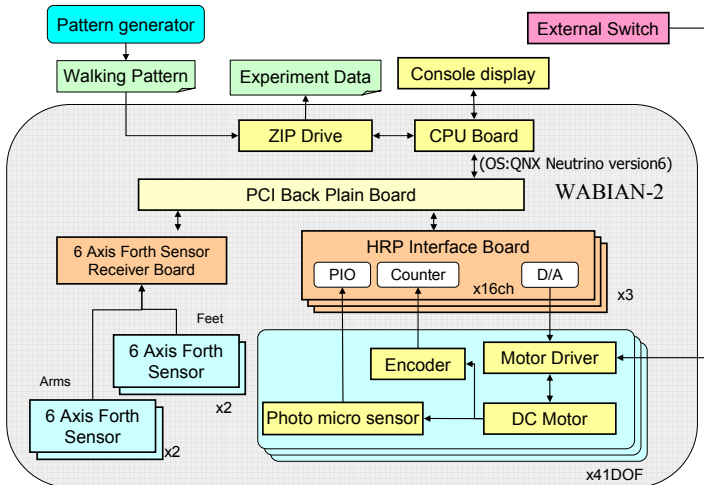
walk- assist machine were carried out. In these experiments, the robot system under development without the neck and the hands actuator system, and the outer coverings, was used. The experiments were conducted with a step cycle of 0.96 s/step, a step height of 0.03 m, a step length of 0.20 m, and three different heights of arm rests of the walk-assist machine that were varied every 0.05 m from 0.85 m to 0.95 m. The walking styles employed in these experiments are conventional walking described above.

The results showed that stable walking with all step lengths is possible. Figure 13 shows pictures of this walking experiment with an arm rest height of 0.90 m/step. Figure 14(a) and (b) show the graphs of experimental data with regard to the reaction forces applied to the right arm and the right foot in the experiments. The average and maximum forces observed in the experiments are summarized in Table 4.

C. Discussion of experiments with a walking assist machine

Figure 14 and Table 4 show that the forces applied to the right arm are increased as the armrest of the walk- assist machine is set lower. On the other hand, the forces applied to the foot are decreased in this case. These results imply that the adjustment of the height of the armrest can adjust load distribution between the upper limb and lower limb.
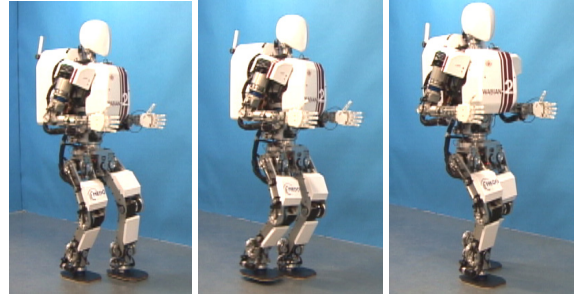

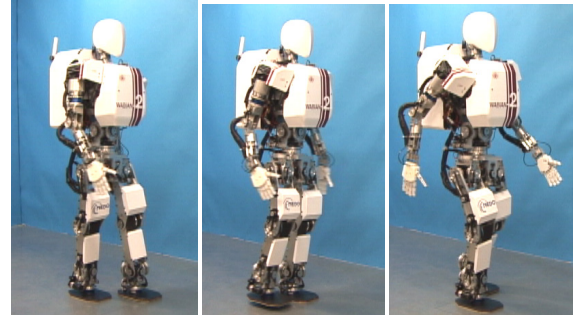Figure 11 Conventional walking
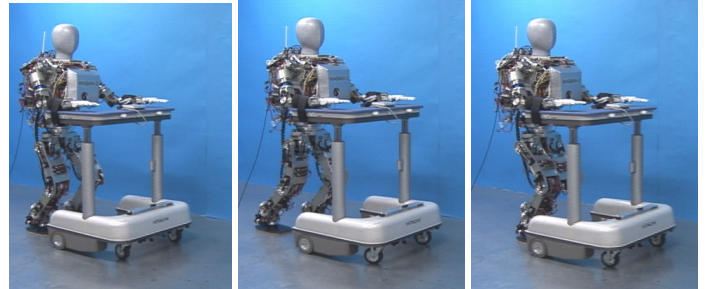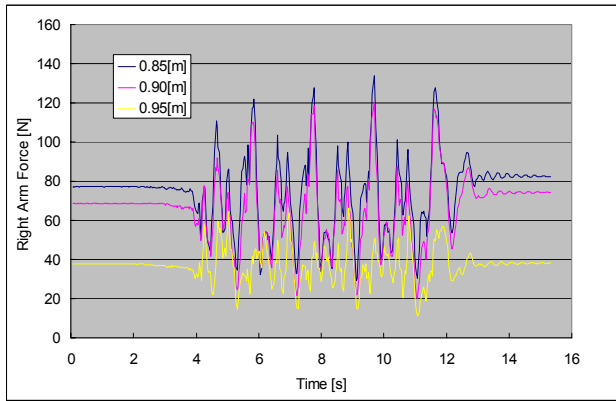

Figure 12 Stretch walking

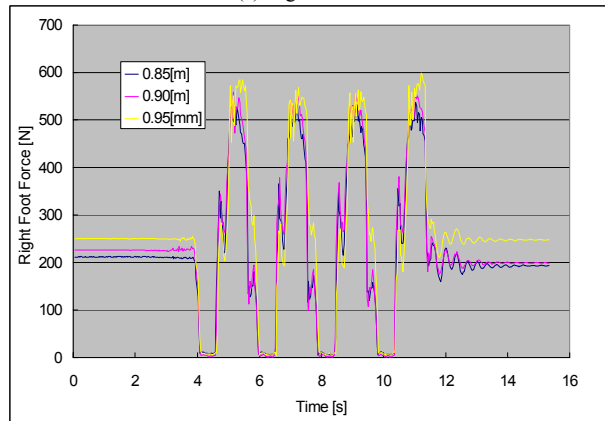Figure 13 Walk with a walking assist machine

Figure 10 Control system of WABIAN-2

(a) Right forearm

(b) Right foot

Figure 14. Reaction forces data

Table 4 Reaction forces data in walking phases

Height of arm rest	Forearm		Foot	
	Average	Maximum	Average	Maximum
0.85m	69.6 [N]	134.0 [N]	240.1 [N]	537.3 [N]
0.90m	60.1 [N]	120.0 [N]	251.4 [N]	558.1 [N]
0.95m	36.2 [N]	66.1[N]	265.6 [N]	598.4 [N]

In addition, some clinicians frequently commented the following: In a general clinic, the initial position of the armrests is set according to the height of the user's elbow; however, if the user has no handicap, it is set higher than the initial position. If the user has lower-limb disability such as a person who requires a cane to walk, the height of the armrest is decreased. These results show that WABIAN-2 can provide quantitative data, which supports qualitative clinical opinions.

VI. CONCLUSION AND FUTURE WORK

This paper describes the development of a novel humanoid robot that can be used as a hardware simulator for human motion. This robot has 7-DOF legs, a 2-DOF waist, a 2-DOF trunk, and 7-DOF arms. In the development of this robot, a new design principle for a robot that can use a walk-assist machine is proposed. Moreover, a method for a redundant trunk motion in order to control forearms is proposed. Mechanical design and the effectiveness of the control method of the robot are confirmed through several types of experiments.

In the near future, it is necessary to utilize walking parameters, such as foot trajectory, and ZMP trajectory, in order to realize an efficient walking motion. Further, a hardware simulator system capable of evaluating the functioning of machines or robots will be proposed. Moreover, the effectiveness of this proposal will be verified through many experiments.

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