Some Issues in Humanoid Robot Design

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1 Introduction

Even though the market size is still small at this moment, applied fields of robots are gradually spreading from the manufacturing industry to the others in recent years. One can now easily expect that applications of robots will expand into the first and the third industrial fields as one of the important components to support our society in the 21st century. There also raises strong anticipations in Japan that robots for the personal use will coexist with humans and provide supports such as the assistance for the housework, care of the aged and the physically handicapped, since Japan is the fastest aging society in the world.

Consequently, humanoid robots and/or animaloid robots have been treated as subjects of robotics researches in Japan such as a research tool for human/animal science, an entertainment/mental-commit robot or an assistant/agent for humans in the human living environment.

Over the last couple of years, some manufactures started to develop prototypes or even to sell mass production robots for the purposes mentioned above, such as the SONY’s pet robot AIBO and the small size humanoid robot QRIO, the TMSUK’s tele-humanoid robot TMSUK04 and the TMSUK-SANYO's home utility robot ROBORIOR, the HONDA’s humanoid robot ASIMO, the TOYOTA’s partner humanoid robots, the NEC’s information agent robot PaPeRo, etc. Most of those robots have some lifelikeness in their appearances and behaviors. Moreover, AIST, METI of Japan launched some national projects, such as Humanoid Research Project (HRP) in 1998 and the New Generation Robot Project in 2004 to develop humanoid robots and service robots, to accelerate the market growth of personal and service robots in the near future.

On the other hand, Waseda University, where we belong to, has been one of the leading research sites on humanoid robot research since the late Prof. Ichiro Kato and his colleagues started the WABOT (WAseda roBOT) Project and produced the historically first humanoid robots WABOT-1 that could bipedal-walk in 1973 and the musician robot WABOT-2 that could play the electric organ in 1984. One of the most important aspects of our research philosophy is as follows: By constructing anthropomorphic/humanoid robots that function and behave like a human, we are attempting to develop a design method of a humanoid robot having human friendliness to coexist with humans naturally and symbiotically, as well as to scientifically build not only the physical model of a human but also the mental model of it from the engineering view point.

Based upon the research philosophy mentioned above, we have been doing researches on humanoid robots, such as the Biped Walking Robots as WL(Waseda Leg) series and WABIAN(WAseda BIpedal humANoid) series, Mastication Robots as WJ(Waseda Jaw) series, Flute Player Robots as WF(Waseda Flutist) series, Emotion Expression Robots(Waseda Eye) series, Speech Production Robots as WT(Waseda Talker) series, etc. In this paper we introduce the mechanical design of the latest bipedal humanoid robot WABIAN-2 and the emotion expression humanoid robot WE-4RIII as shown in the Figure 1 and 2.

2 Bipedal Humanoid Robot WABIAN-2

In retrospect, many researchers have studied the control and mechanism of biped robots in recent years (Sakagami et al. 2002), (Nishiwaki et al. 2000), (Nishiwaki

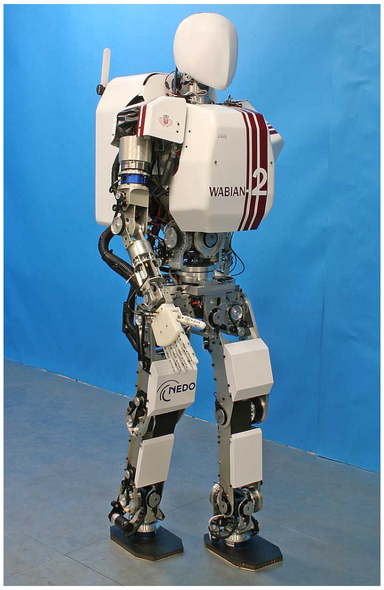


Fig. 1. Bipedal humanoid robot WABIAN-2

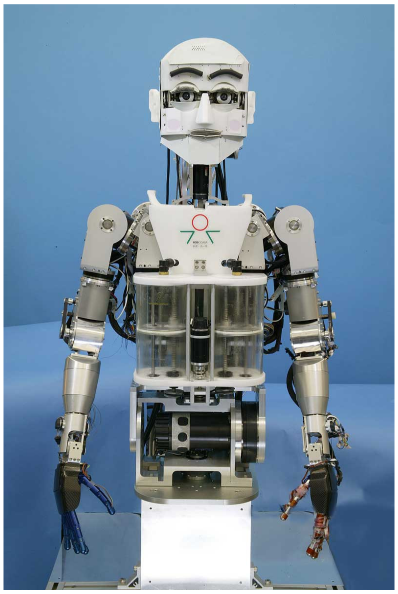


Fig. 2. Emotion expression humanoid robot WE-4RII

et al. 2002), (Löffler et al. 2003). These humanoid robots assimilated dynamic and stable walks. However, there are a few studies on human-like upper body. The Japanese National Institute of Advanced Industrial Science and Technology with cooperation of Kawada Industries, Inc., have developed HRP-2 and HRP-2P, which have 2-DOF trunk system and implement falling down motion in a positive way and rising from a lying position (Kaneko et al. 2002), (Fujiwara et al. 2003). This robot effectively bent its trunk in the experiments. The humanoid research group of Waseda University has also been studying biped humanoid robots since 1966. Research on the WABIAN (WAseda BIpedal humANoid) series had set walking with 3-DOF trunk motion and walking with 3-axis ZMP (Zero Moment Point) compensation using the trunk (Lim H et al. 1999), (Lim H et al. 2002).

In advance of this study, we already have developed a new biped walking robot named WABIAN-2/LL (WAseda BIpedal humANoid-2 Lower Limb). Moreover, we have developed an algorithm that enables the robot to stretch its knees in steady walking avoiding singularity by using waist motion, and carried out stretch walking experiment by using this robot (Ogura Y et al. 2004), (Ogura Y et al. 2004). WABIAN-2/LL without upper limb originally developed as a lower limb system for a humanoid type robot WABIAN-2(WAseda BIpedal humANoid-2). In this chapter, we propose this new humanoid robot WABIAN-2 which has two 7-DOF legs, a 2-DOF waist, a 2-DOF trunk, and two 7-DOF arms. In the development of the robot, new design principle for a robot which can be used as a walking assist machine for a handicapped or elderlies is set as the first goal of this study.

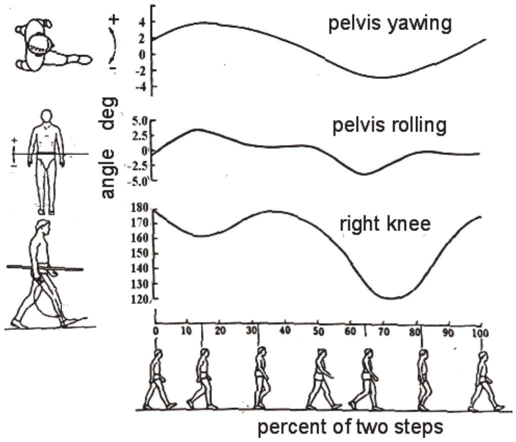


Fig. 3. Human's pelvis and knee motion (Klopsteg et al. 1963)

2.1 Design Concept

2.1.1 Human motion

Human body mechanism basically comprises bones as rigid links, cartilage that lines the 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, we determined that the primary goal of the mechanical design is to develop a robot that can imitate equivalent human motion.

Klopsteg et al. have proposed the result of the gate analysis of humans **(**Klopsteg et al. 1963**)**. Figure 3 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 or mental 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 the roll and yaw axes. These hip movements have to be independent in its trunk position.

Moreover, a study of gait analysis and bio mechanics has reported about pelvis motion. In steady walking, Pubic symphysis, the two hipbones combined by a cartilage, moves like a crank joint. According to this motion, the two hipbones are

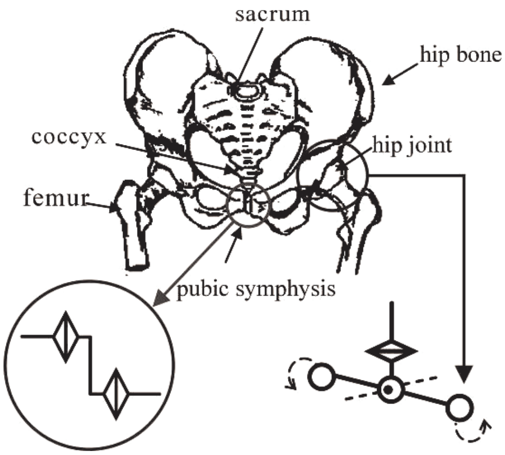


Fig. 4. Pelvis of a human

sliding on each other. Therefore, we considered that the hip joint is able to make two dimensional circular motions as shown in Fig.4.

On the other hand, human can move its trunk independently from the hip motion. The Japanese Association of Rehabilitation Medicine (JARM) and the Japanese Orthopaedic Association (JOA) have established basic roles of representation and measurement method for range of motion (ROM) **(**Klopsteg et al. 1963**)**. The general idea of ROM does not always means joints or articulation. These ROM measurements had carried out in a sitting position or with instruments to fix the pelvis in order to avoid the pelvis movement.

It is essential for a human motion simulator to have the ability to move its trunk. For example, trunk motions are used for rising a sitting position, walking with a limp, walking with movements are useful, not only for keeping the whole body balance, in other words, compensate motion for ZMP on contact ground, but also for absorption mechanism of positional error in the case that the robot grasps or leans against something on the ground. When the robot leans against a rail or use a walker or a walking assist machine, the system composed to the robot and the instrument becomes a statically indeterminate structure. Such a system will need some redundant DOF and a robust control method. It is considered that a human usually use its trunk motions unconsciously in these cases.

2.1.2 DOF Configuration

Figure 5 presents the DOF configuration of the new humanoid robot having 41 DOFs in Total. In this study, the initial pose of the robot is defined as standing straight, and rotational direction of each joint is defined by using inertial coordinate system fixed on the ground as shown in Fig. 5 (Ogura et al. 2004).

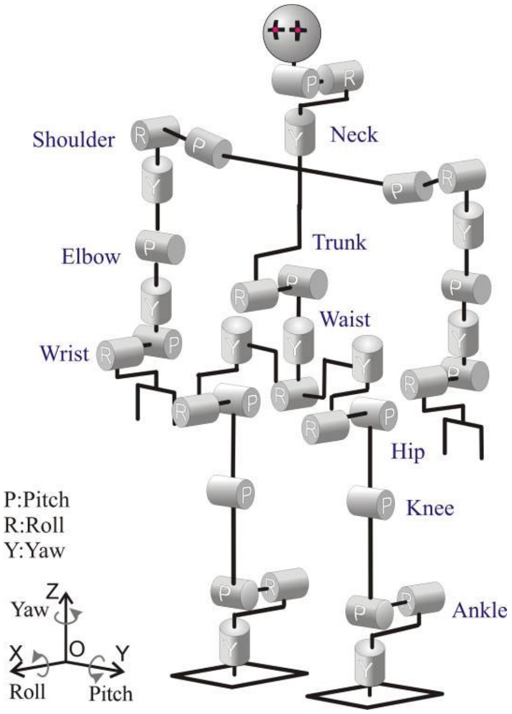


Fig. 5. DOF configuration of WABIAN-2 having 41 DOFs in total

WABIAN-2 has 7-DOF legs and arms like a human. Although many researchers have studied 7-DOF arms, there are few studies on mechanisms and control method of 7-DOF legs. The ankles of almost all conventional biped humanoid robots consist of the pitch and the roll axes. 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. 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 can rotate knee orientation independently from 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.

In 2-DOF waist system, the roll axis and yaw axis should be perpendicular to each other, and crossing 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 laid on the lower limb side and the yaw joint on the trunk side. This makes the yaw joint able to be used as yaw rotation for both the hips and the trunk. This DOF configuration of waist and trunk gives substantial 3-DOF trunk motions.

2.2 Mechanisms

2.2.1 Overview

The whole mechanical design was done by using a 3D CAD software, SolidWorks 2003. 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 joint consists of a DC motor, a Harmonic drive gear, a lug belt and two pulleys. This double speed reduction mechanism allows high reduction ratio, and also a joint axis to be set apart from a motor axis. Therefore, we could design a human-like joint mechanism without a big projection. In this paper, we mainly focus on the development of the waist, trunk and arms.

Specifications of each joint such as maximum torque and rotating speed are designed based on results of software simulations. Those results were computed by using Newton-Euler's Method and estimated mass distribution. The several types of the simulations were carried out for the determination of the joint specification. The details are described as follow.

2.2.2 Waist and Trunk

Figure 6 and 7 show the 2-DOF waist and 2-DOF trunk system. 2-DOF waist combination of a roll and a yaw joint is attached on the middle between the hip joints. 2-DOF trunk having a pitch and a roll joint is assembled over the waist.

In the design of the trunk some simulations have been conducted. The simulation tested the maximum torque for the trunk roll and pitch joint. During each walking step the robot moves its trunk in a way that can keep it balance. There are two type

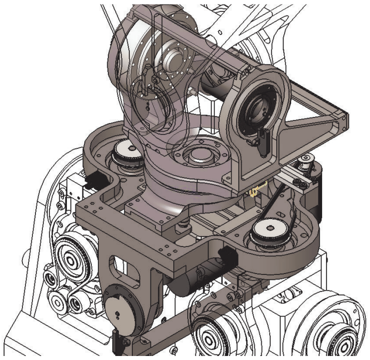


Fig. 6. Waist mechanism

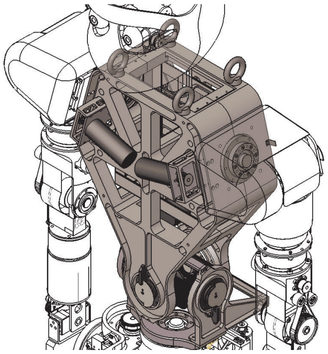


Fig. 7. Trunk mechanism

of simulation. First, static modeling which determined the maximum angle. Second, dynamic modeling which calculated the angle during the time used to complete one walking cycle. The maximum angle that can be determined by dynamic modeling is half the maximum movable angle determined by static modeling. Figure 8 shows a static model of the trunk in form of link and mass block. There are two models, one from side plane (Pitch axis) and other from front plane (Roll axis).

2.2.3 Arms

The arm of WABIAN-2 has 7-DOF. Figure 9 shows the 3D-CAD. The arms were designed in such a way that can support the robot balance while it is walking. It includes three actuators for fingers that can bend like human's hand fingers. Moreover, the arms were designed to hold the robot weight while it leans on a walking assist machine.

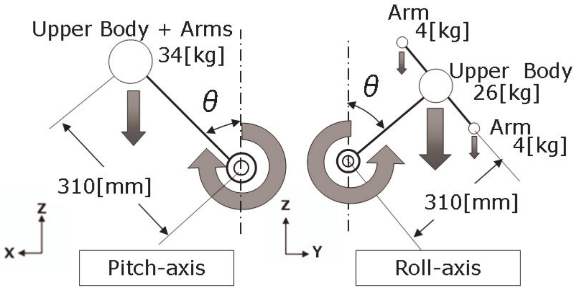


Fig. 8. Static Mechanics Model for Trunk Design

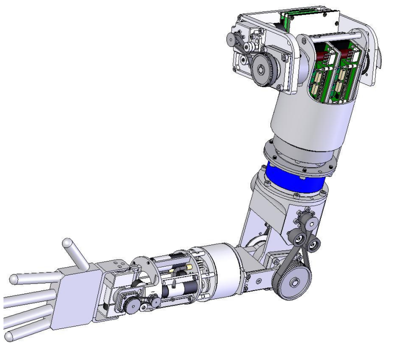
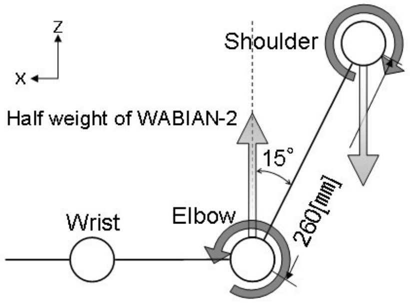


Fig. 9. Left Arm Mechanism

Since the robot could lean on a walking assist machine, most of the robot weight will become on both the elbow. In order to determine the suitable angles of the arms some software simulation were conducted. Figure10 shows software simulations for determination of specification of upper limb mechanisms. In this simulation, the robot leans on a walking assist machine using its forearms. The elbow angle is 15deg from a posture bend at right angle, when the arm supports a half weight of the robot (30kg, the two arms support a whole weight of the robot (60kg)).

3 Emotion Expression Humanoid Robot WE-4RII

Humans take a certain posture in their communication. For example, when they are happy or cheerful, they take a posture in which the activity is high such as moving arms upward or opening the arms. When they are angry, they square the



shoulders. When they are tired or sadness, they shrug the shoulder or close the arms (Hama et al. 2001). Therefore, the emotion and mental state are closely related to the human posture and behavior. And, human obtain many information from partner's posture in their communication. In this situation, the human arms play an important role.

We can control the usual 6-DOFs robot arms' tip position as accurately as human's arm. But, all their joint angles are fixed according to the inverse kinematics. By the way, humans have 7-DOFs arms consisting of 3-DOFs shoulder, 1-DOF elbow and 3-DOFs wrist. However, we considered that there is a center of rotation in the base of shoulder, and the shoulder joint itself moves up and down and moves back and forth so that humans square and shrug their shoulders. We considered that these motions played a very important role in the emotional expressions. Therefore, we tried to develop more emotional expressive humanoid robot arms than the usual 6-DOFs robot arms.

3.1 9-DOFs Emotion Expression Humanoid Arm

Figure 11 shows the 9-DOFs Emotion Expression Humanoid Arm developed in 2003 (Miwa et al. 2002), (Miwa et al. 2003), (Miwa et al. 2004). It has 2-DOFs at the base shoulder, 3-DOFs at the shoulder, 1-DOF at the elbow and 3-DOFs at the wrist. The robot arm can move each joint as widely as human for the more human-like emotional expression. Moreover, we designed the new robot to have the same dimension as the averaged male for the natural appearance using a 3D CAD software, SolidWorks 2003, like the WABIAN-2 design.

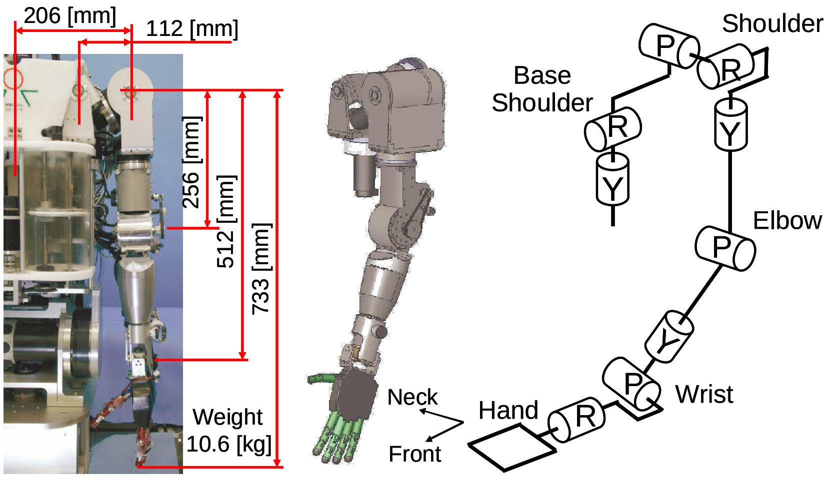


Fig. 11. 9-DOFs Arm Mechanism of WE-4RII and Its DOF Configuration

3.1.1 Base Shoulder

The base shoulder consists of the yaw axis and roll axis. They cross at the right angle. The yaw axis is driven by a direct driven mechanism with DC motors and harmonic drive systems. On the other hand, the roll axis is driven by a direct driven mechanism with an AC motor and a harmonic drive system because the roll axis needs the higher torque than the other axis to lift up the robot arm.

3.1.2 Shoulder

The shoulder has the pitch, roll and yaw axes. All axes are driven by a direct driven mechanism with DC motors and harmonic drive systems. In the case that the three shoulder axes cross at the identified position at the right angle, the posture where a robot horizontally stretches its arm is the singular point. So, we can’t solve the inverse kinematics geometrically. However, the posture which the arm is lengthened just beside can be taken in everyday action. Therefore, we leaned the pitch axis 30 [deg] from the horizontal plane as shown in Figure 12 in order to reduce to move the arm to the singular point problem in a common use range. However, this mechanism couldn’t avoid singular point problem completely. So, we avoid moving the tip of the arm to the singular point by software.

3.1.3 Elbow

The elbow has 1-DOF. In order to reduce the sense of incongruity on appearance realizing the same movable range with human, we adopted a belt driven mechanism, in which an output axis of a motor connects with a harmonic drive system by a timing belt.

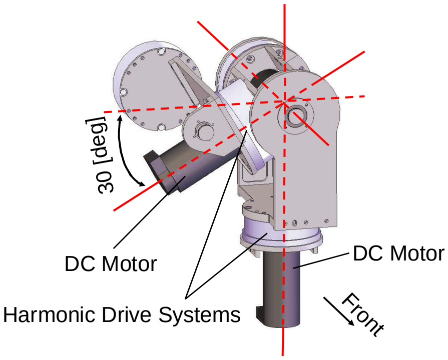


Fig. 12. Shoulder Mechanism of WE-4RII

3.1.4 Wrist

The wrist has the pitch, roll and yaw axes. They cross at the identified point at the right angle. The pitch axis is driven by a belt driven mechanism and the yaw and roll axes are driven by direct driven mechanism with DC motors paired with planetary gears.

3.1.5 Hand

The hands called RCH-1 (RoboCasa Hand No. 1) were designed in an international collaboration at RoboCasa which was established in 2003 between Waseda University in Japan and Scuola Superiore Sant' Anna in Italy (Zecca et al. 2004). RCH-1 is an under actuated hand having 6 DOFs of Motions while having 16 degrees of kinematical degrees.

3.2 Integration to Humanoid Robot WE-4RII

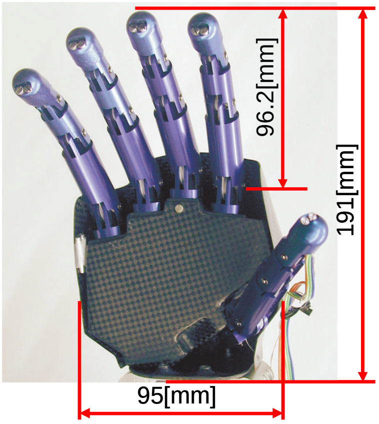
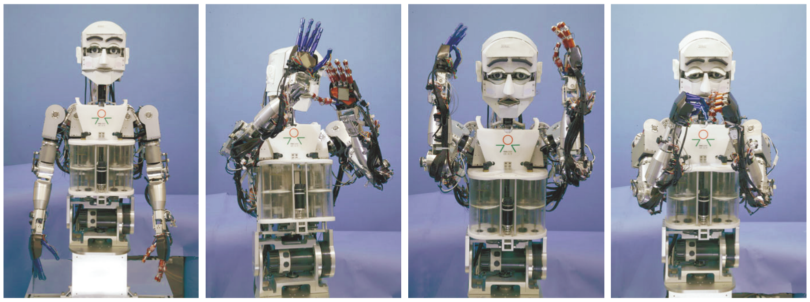


Fig. 13. RCH-1 Hand

We developed the whole Emotion Expression Humanoid Robot WE-4RII shown in Figure 2 by integrating the 9-DOFs Emotion Expression Humanoid Arms and the 6-DOFs Humanlike Hands RCH-1 into the Human-like Head Robot WE-4. WE-4RII is 0.97 [m] tall and weigh 59.3 [kg]. And, it has 59-DOFs in total shown in Table 1. By adding the arms and the hands, WE-4RII could express its emotion with not only the facial expression but also the upper-half body including the waist, arms, hands and neck. Moreover, the motion velocity is as important as the posture in emotional expression. Therefore, we controlled both the posture and the motion velocity for the effective emotional expression. Figure 14 shows the emotional expression exhibited by WE-4RII.

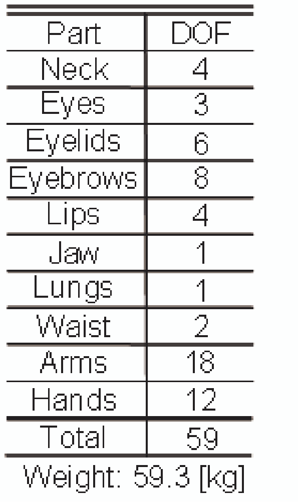


(a) Neutral (b) Disgust (c) Fear (d) Sadness

(e) Happiness (f) Surprise (g) Anger

Fig. 14. Presented seven basic emotions by WE-4RII

Table 1. DOFs of WE-4RII



Part	DOF
Neck	4
Eyes	3
Eyelids	6
Eyebrows	8
Lips	4
Jaw	1
Lungs	1
Waist	2
Arms	18
Hands	12
Total	59

Weight: 59.3 [kg]

4 Conclusions and Future Work

This paper describes how we designed the two humanoid robots WABIAN-2 and WE-4RII. WABIAN-2 has 7-DOF legs, a 2-DOF waist, a 2-DOF trunk, and 7-DOF arms. In the development of the robot, new design principle for a robot which can use walking assist machine is proposed. In the near future, we shall propose a hardware simulator system capable of being applied to the evaluation of welfare machines or robots. In order to demonstrate the validity of the proposal, we are presently preparing an experiment in which a biped humanoid robot uses a walking assist machine. The measurements of the current or force/torque sensors will present a quantitative clarification of the manner in which the machine assists humanoid walking. We also designed the 9-DOFs Emotion Expression Humanoid Arms as well as the 6-DOFs RCH-1s, and integrated them into the Emotion Expression Humanoid Robot WE-4R. We also have developed an emotion expression control method for WE-4RII and that was presented in IROS 2004. In the future, we shall increase the emotional expression patterns and robot behaviors. And, we also shall introduce the behavior model which autonomously determines and outputs the most suitable behavior or emotional patterns according to the situation which is one of the essential functionalities of an intelligent robot to interact with humans.

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