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A Musculoskeletal Flexible-Spine Humanoid Kotaro Aiming at the Future in 15 years' time

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1. Introduction

Recently, humanoid research and development are widely under way. There are, however, still a lot of problems we have to solve. One fundamental problem is contact with a human. Robots coexisting with human beings have contact with human on a daily basis, and they are required to be entirely safe. Another fundamental problem for human coexisting robots is the diversity of humans' fields; diversity means that of tasks and that of the environment. We propose human-like body structure as a possible solution. It is comparatively easy to install physical flexibility to musculoskeletal robots, because their joints are passive. Muscle driven structure has advantage for increasing number of serially connected joints based on the 'coupled-drive' mechanism (Hirose et al., 1989). This paper presents the concept of our new humanoid Kotaro, describes the mechanical design including the actuation system and sensors, shows the demonstrations performed at the EXPO'05, and discusses the future perspectives of the research.

2. Humanoid and Human in Year 2020

The title of the chapter goes "aiming at the future in 15 years' time." This comes from the theme of "Prototype Robot Exhibition" at the World EXPO'05. The exhibition was a part of "Project for the Practical Application of Next-Generation Robots" organized by NEDO (http://www.nedo.go.jp/english/). The purpose of the exhibition was 'to look for original technologies from Japan that could lead to the creation of robots with application in a wide variety of different environments, including households and offices, by 2020,' according to NEDO. Our proposal for the aim is musculoskeletal humanoids. Humanoids need to be softer and safer. They will also have to adapt to various environments and tasks. Musculoskeletal humanoids with many sensors have potential to solve the problems. In this section, the characteristics of our proposal are described.

2.1 Interaction with Humans

(a) Physical softness
A robot in a human environment needs physical softness to avoid hurting humans and surroundings, as well as force-feedback control such as impedance control (Hogan, 1985). A human can control mechanical impedance by antagonistic muscles (Hogan, 1984). We could consider the softness of structure. Human's bone, which is not as stiff as metals, gives us an inspiration. A basis of controlling machines has been based on precision and rigidity. Assuming

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mechanical flexibility may need a new paradigm of design and control of machines; human and animals do not seem to use the same basis in design and control of their body.

(b) Sensing of contact information

Tactile sensors are necessary for human environment. Mechanical softness of the surface is also important for contact with human. A problem related to tactile sensors of humanoid robots is difficulty of covering whole-body; covering around joints, fitting to complex surfaces, and difficulty of wiring. In this paper, we propose two types of tactile sensors. One is fleshy soft sensor and the other is bandage type sensor (see 5).

(c) Multimodal communication

There will be also social interaction with human. Robots ought to have visual and auditory senses and vocal function. We also have to think about the design of human-coexisting robots.

2.2 Diversity of Human's Field

There are numerous variety of tasks people expect robots to do at their houses. The versatility will greatly help the robots become widely used. The robots will need to adapt to unarranged environments. The necessity and usefulness of human-form (of the robots) is this. The number of joints is very important for achieving versatility. A human unconsciously uses a large number of his joints efficiently. The range of degrees of freedom (DOF) of current humanoid robots is from about 20 to about 40, while a human has more than 200 DOF.

2.3 Musculoskeletal Humanoid Approach

We have designed and developed a new musculoskeletal humanoid Kotaro (Fig.1), to show the possibility of musculoskeletal humanoid at the exhibition at the EXPO (Mizuuchi et al., 2005b). Kotaro has a passive skeletal structure with many joints and motor-actuated muscles, and it has numerous sensors including muscle-tension sensors, rotary encoders as mus-cle-length sensors, motor-current sensors, tactile sensors, vision, audition, gyros, accelerometers, and so on (Mizuuchi et al., 2006).

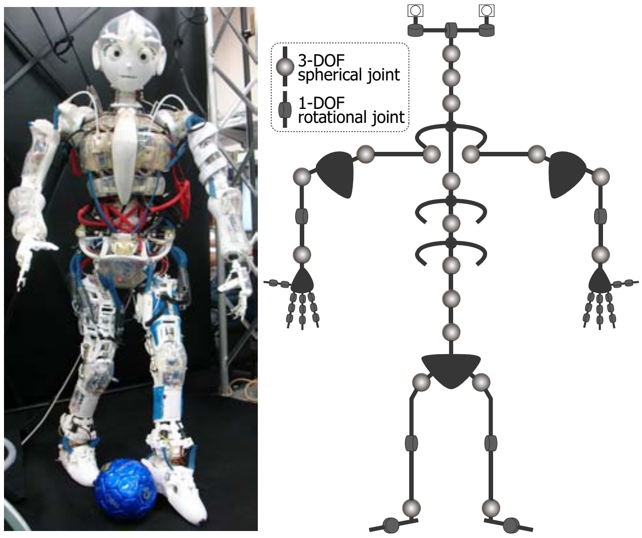

Fig. 1. Kotaro's photograph (left) and the arrangement of joints (right).

Musculoskeletal structure has advantages when realizing an articulated structure and installing mechanical flexibility. If an articulated structure consists of serial rotational joints actuated by rotational motors, then each motor has to generate torque enough to move or hold the mass and inertia of the descendant parts. In case of a tendon-driven structure, on the other hand, several actuators cooperatively work for moving one joint, as well as each actuator can determine the posture of one joint. A muscle-driven robot can have multi-articular muscles, which drive more than one joint. Human's body has several kinds of such muscles.
Another advantage of musculoskeletal robots is easiness of installing mechanical elasticity and viscosity. Joints of muscle-driven skeletal robots are, in general, passive joints, and the structure around a joint is relatively simple.

3. Design and Implementation of Kotaro

Approximate height of Kotaro is 130[cm], and weight is about 20[kg] excluding power source and main computer which is placed outside the robot. In this section, Design and implementation of Kotaro is described.

3.1 Arrangement of Joints

The right figure of Fig.1 shows the arrangement of Kotaro's joints. There are 3-DOF ball-and-socket joints and 1-DOF rotational joints. We used ball-and-socket joints for most Kotaro's joints. Total degrees of freedom of joint angle space are 91. The spine consists of 5 spherical joints, and the neck has 3. A leg has 8 DOF and an arm has 13. The structure of the shoulder, which is inspired from human's shoulder, consists of a collarbone and a bladebone, for expanding the movable range of the arm and increase inner space inside the chest (Sodeyama et al., 2005). Each four-finger hand has 11 DOF: 2 rotational joints for the thumb, and 3 rotational joints for the other fingers. Two color cameras are installed in the eye balls, which has three degrees of freedom; panning angles are independently controllable and tilting is synchronized.

3.2 Reinforceable Muscle Humanoid

Yet another advantage of musculoskeletal robots is configurability of muscles. We have proposed a concept of Reinforceable muscle humanoid (Mizuuchi et al., 2004, 2005a). Joints are passive and we do not have to decide how to drive the joints and how much power to allocate at the design stage. It will be quite difficult to determine the actuator configurations beforehand, because the expected tasks for the robots in humans' life field are very broad. In case of a human or an animal, muscles are strengthened as growing up or by training.
We have developed a new muscle unit which contains a 4.5W DC motor, pulleys, a tension sensor using strain gauges, an amplification circuit board and a thermometer. Fig.2 shows the unit. The black cords are chemical ropes. Fig.3 is a picture of a part of Kotaro's body around hip joints, where some muscle units are attached. We can easily add/remove units and modify the attaching positions of some units. There are many small holes on bones (structure parts) for attaching wires. All of higher power 20W motors and some of 4.5W motors to wind up the tendons are placed inside the bones as initial muscles, while others are reconfigurable muscle units.

Fig. 2. A newly-developed, sensors-integrated muscle unit.

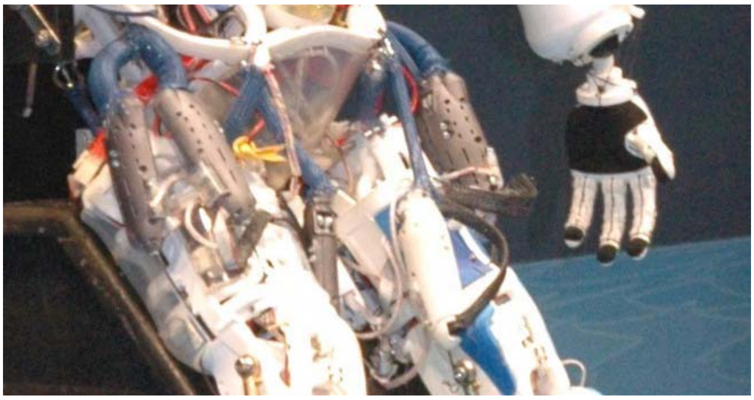

Fig. 3. The muscle units attached around both crotch joints.

3.3 Flexible Spine

Human's spine with 24 joints has most degrees of freedom among human's body. We have assigned five spherical joints to Kotaro's spine. Each of upper three vertebrae has a rib bone (costa), which enlarges the moment arm and increase the torque around spine joints. In addition, rib bones make space inside the chest for installing motors and boards. Every vertebra has at least four points for attaching an end of a muscle-tendon. At least 4 tendons are needed to determine the posture of a spherical joint. There are 4 tendons between the pelvis and the lowest vertebra, and 4 between the pelvis and the second lowest vertebra. 4.5W motors installed on the pelvis pull these 8 muscle-tendons. There are 4 tendons between the lowest costa (third vertebra) and the middle costa (fourth vertebra). 4.5W motors installed in the lowest costa pull these 4 muscle-tendons. There are four main stomach muscles that are connecting between the pelvis and the middle costa (see Fig.4), pulled by four 20W motors in the pelvis.

Kotaro's spine has physical softness. There is a part made of silicone rubber between every neighbor vertebrae. It is like human's interspinal disk, which is indicated as 8 in Fig.5. The figure shows the structure of human's spine (Kapandji, 1974), seen from the left side. The silicone rubber disks have elasticity and viscosity. Fig.6 is a photo of the pelvis and lower spine. In human's spine, there are ligaments (11 to 16 in Fig. 5) between the vertebral bones. Kotaro's spine has also tension springs between joints as ligaments. These rubbers and springs give the spine a force returning to the initial posture against gravity. This is also an effect of elasticity and helps the actuators.

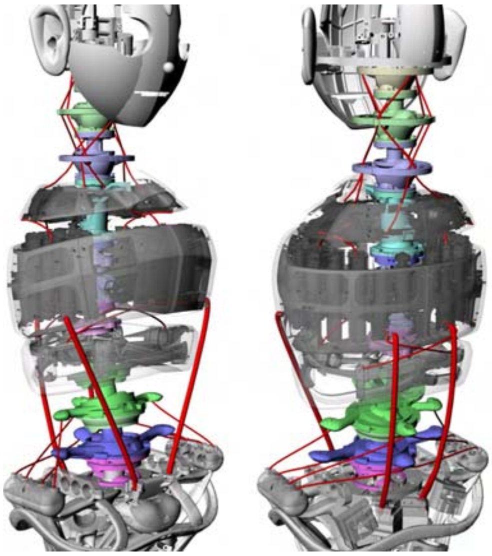

Fig. 4. Bones (gray) and muscles (red) of Kotaro's torso.

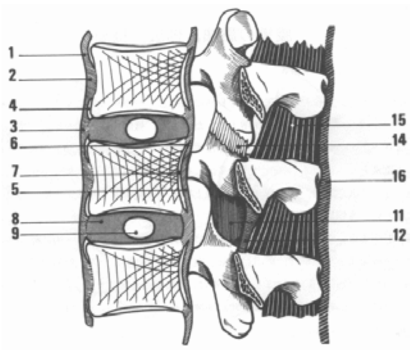

Fig. 5. Human's spine structure seen from left side (Kapandji, 1974).

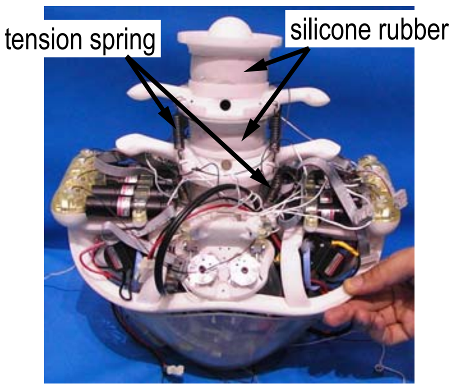

Fig. 6. Elastic and viscous elements between joints.

3.4 Collarbone and Bladebone

Kotaro's shoulder structure has been inspired from human's one. It consists of a collarbone and a bladebone. The advantage of this is the wide movable range and large space inside the chest (Sodeyama et al., 2005). Though the movable range of shoulder's spherical joint is not so wide, the center of rotation of the shoulder joint, which is on the shoulder blade, can be moved according to the movement of the bladebone and collarbone. The center of rotation of the movement of the shoulder joint is near the center of the body. The bladebone moves on the surface of the back chest. These bone structures are actuated by muscle-tendons. Fig.7 shows the shoulder structure of Kotaro. Fig.8 shows two postures of Kotaro's left shoulder and arm. In arm-raising motion, human's bladebone start moving when the upper arm is raised to a certain extent. In the pictures, Kotaro is doing similar movement.

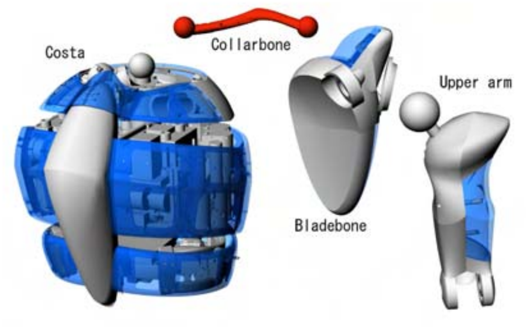

Fig. 7. Collarbone and bladebone.

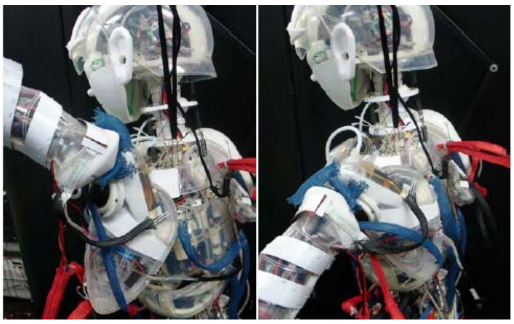

Fig. 8. A coupled movement of bladebone and upper arm.

3.5 For Light and Strong Bones

Though we use muscle units for reinforceability, some inevitable muscles are installed inside bones. Bones are needed to be tough and light, and possible to hold motors and circuit boards inside. Kotaro's bones have been designed based on a concept namely 'hollowed mesh skeleton.' Fig.9 shows some bones; these are the pelvis, right thighbone, and so on. The radius of a bone is relatively large as a bone of an endoskeletal structure, in order to make space inside. The shapes of the holes of the mesh are designed so that the inner parts such as motors and circuit boards can be installed through the holes. The cross section of each mesh is T-shape or X-shape for increasing strength. Most bones are designed as single-piece parts. To form the structural parts, we used some rapid prototyping (RP) methods. Main parts were made by selective laser sintering (SLS) method, and transparent parts were made by stereolithography.

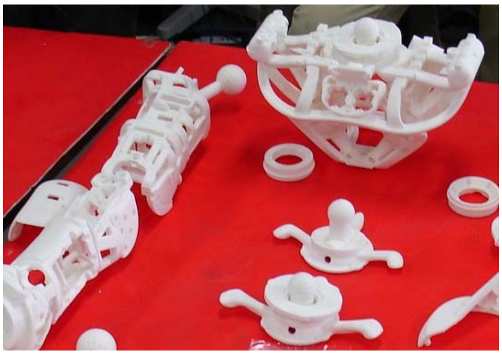

Fig. 9. Some "bones" of Kotaro.

3.6 Muscle-driven Head for Multi-modal Communication

Fig. 10 shows Kotaro's muscle-driven head for multi-modal communication with humans. In each eyeball, there is a USB2 color camera. Eyeballs are also tendon-driven. There are three actuators for eyes; the left-and-right movement is independent, and up-and-down is synchronized. There are two microphones in ears and one speaker near the mouth. These multimedia devices use USB, and are connected to a remote host PC through one USB cable. The same USB 480Mbps line is used for all the other sensors and actuators of the whole-body. There are also gyro sensors and accelerometers in the head.

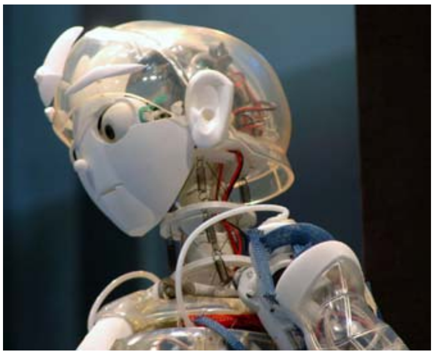

Fig. 10. Muscle-driven head for multi-modal communication.

4. The Sensing System for Human Contact

4.1 A Soft and Fleshy Tactile Sensor Using Conductive Rubber Foam

We have developed a soft and fleshy tactile sensor using force-sensitive conductive rubber foam (Fig. 11). The black element in the figure is the rubber foam. There are electrodes inside the 3D shape. By measuring the resistance between electrodes, tactile information can be detected. In addition, there is a possibility of detecting the change of the 3D shape. Fig.11 shows the sensors. The right photo is Kotaro's left hand; the palm and fingertips are made of the conductive rubber and there are electrodes inside. An advantage of this sensor is flexibility of arranging the sensing electrodes. If more sensitivity is needed at an area, inserting an extra electrode can improve sensitivity.

Fig. 11. Soft and fleshy tactile sensor using conductive rubber foam.

4.2 A Free Form Tactile Sensor for Covering Whole Body

For attaching tactile sensors on various shape surfaces of a robot, we propose a bandage-shape tactile sensor. This shape can match complex surface, compared with sheet-type tactile sensors. Fig. 12 shows the developed sensor. In the right photo, Kotaro's left arm is covered by this type of sensor. One bandage has 64 sensing points, and wiring forms an 8x8 matrix. Connecting a bandage to a circuit board needs only a 16-line cable. Moreover, we can cut the bandage at any of cutting places for modifying the length without damaging the sensing circuit. This sensor consists of two thin films of flexible circuit boards and a thin film of force sensitive conductive rubber. When the rubber film is pushed, the resistance changes. Analog information of this sensor is also measured by using a small circuit board (Fig. 14).

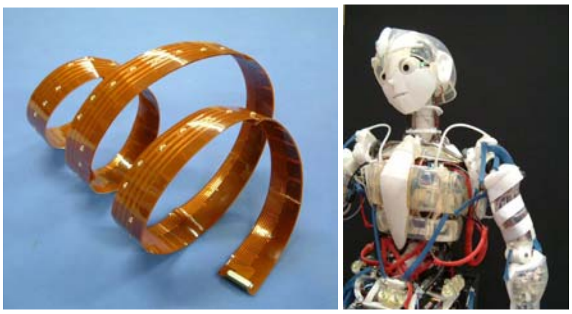

Fig. 12. Free form tactile sensor for covering whole body.

4.3 Posture Sensor for a Ball-and-Socket Joint

Joint angle sensor for a spherical joint has been a problem. We propose a new method for estimating the posture of a spherical joint by observing the ball by a small camera. On the surface of the ball, many spots are drawn. A visual processing unit connected to the camera tracks the movements of the spots and estimates the 3D joint-angle of the spherical joint.

We implemented the sensing mechanism (Urata et al., 2006) by using a very small camera originally for mobile phones, and by using a processor (SH-mobile by Renesas; 10mm x 10mm BGA) also originally for mobile phones. The right photo of Fig. 13 shows the developed boards, the cameral, and a coin. The size of the board is 1 inch^2 (2.54 mm^2). The lower left picture of Fig.13 shows a prototype of the ball, which we made at first. Inside of the socket is dark, so and LED was embedded in the ball. The upper left of Fig.13 shows the schematic of the latest version, which uses and LED, plastic optical fibers, and some color filters for detecting the calibrating position.

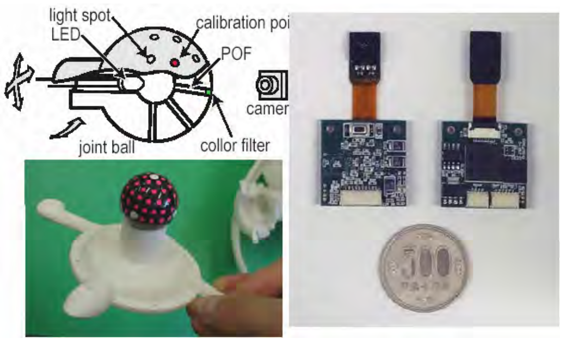

Fig. 13. Posture sensor for ball-and-socket joint using a mobile phone camera and a mobile phone microprocessor.

4.4 Print Circuit Boards for Onbody Information Processing

When the number of actuators and sensors in a robot is increased, it will be better to distribute the circuit boards for efficiency of wiring. We have designed Kotaro's onboard system as a distributed system. We developed several kinds of circuit boards as shown in Fig. 14. The upper left photo shows motor driving boards for four 4.5W motors per a board, and the lower left one shows the boards for two 20 motors per a board. The size of both motor-driving boards is 36mm x 46mm. The upper right photo shows the boards that can collect 384 analog signals per one board (six 64x64 matrices). Every board of these three kinds has a USB1.1 interface (12Mbps). The lower right photo shows small USB2.0 (480Mbps) hub boards (compatible with USB1.1). The hub board has seven downstream ports and one upstream port, and it is able to connect commercial USB2 cameras with 640x480 pixels, USB microphones, USB speakers, and so on. All of the boards have been developed at the Kotaro project. There are about forty circuit boards in Kotaro's body, and only one USB cable is connected to a remote host PC, which manages the whole body of the robot.

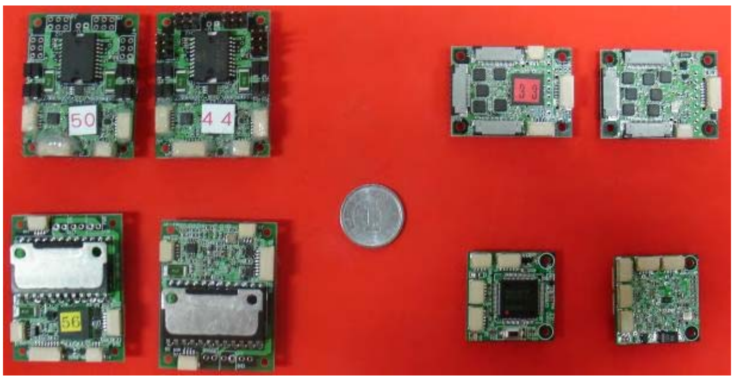

Fig. 14. Developed circuit boards (upper-left: for 4 small motors, lower-left: for 2 middle motors, upper-right: for 384 analog sensors, lower-right: 7-port USB2 hubs).

5. Summary and Conclusion

This chapter has presented the concept and overview of Kotaro project, which aims at showing a proposal of robotics technologies of the year 2020. We joined the Prototype Robot Exhibition of the EXPO'05 held in Aichi, Japan, and performed demonstrations. Fig. 15 shows scenes at the exhibition. Kotaro has 91 DOF including flexible spine. Driving system of the endoskeletal structure is based on a wire-driven system which we call muscle-driven system. Currently it has about 90 motors and it can have up to 120 motors; sensor-integrated muscle units realize the easy addition of muscles. We call this characteristic as 'reinforceability.' Kotaro has physical flexibility by silicone rubber parts and tension springs embedded between joints, to achieve safety, supple motions, and human friendliness in the future. Kotaro has many sensors including muscle-tension sensors, muscle-length sensors, two kinds of tactile sensors, posture sensors for 3D spherical joints, two eyes, two ears, and so on. The skeletal structures are based on the concept 'hollowed mesh skeleton' and made by RP methods.

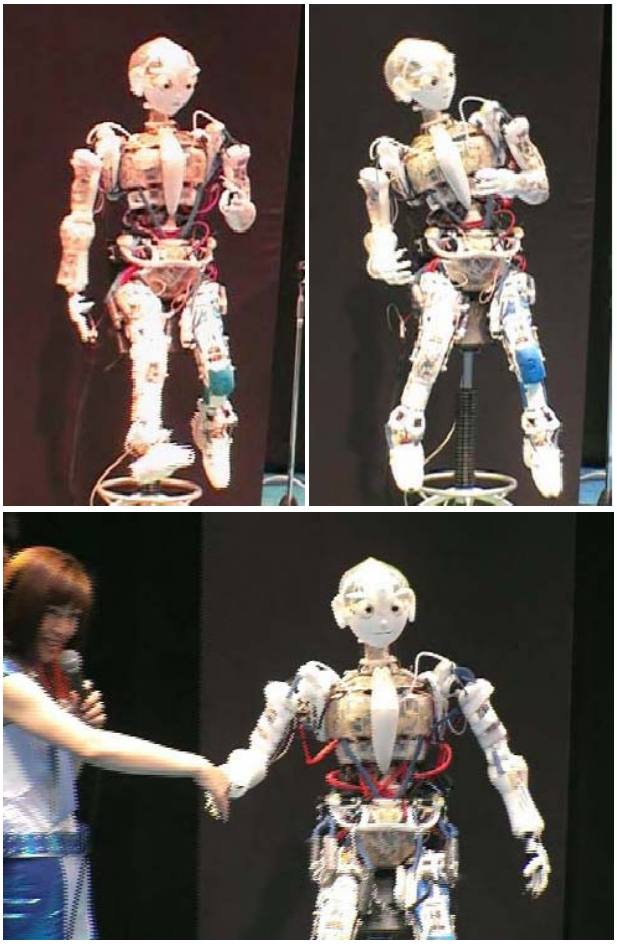

Fig. 15. Demonstration scenes at the EXPO'05 in Aichi, Japan.

We believe that in future robots will be closer to human than present and their bodies should be much more compliant, and we may have to re-think about the structure of robot body fundamentally. We hope Kotaro will be a footstep to a new stage of humanoid robotics. Future problems include realizing various motions using the flexibility of the body, finding out a software system which can manage the complexity of input/output of a robot, a framework of autonomous development like infants, and so on. Fig. 16 shows an ideal image of Kotaro: climbing a tree utilizing the flexible body.

Fig. 16. An ideal image of Kotaro: climbing a tree utilizing the flexible body.

6. Acknowledgment

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