An Advanced Musculoskeletal Humanoid Kojiro

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***Abstract*— We have been promoting a project of musculoskeletal humanoids. The project aims at the long-term goal of human-symbiotic robots as well as the mid-term goal of necessary design and control concepts for musculoskeletal robots. This paper presents the concepts and aim of the project and also shows the outline of our latest results about development of new musculoskeletal humanoid Kojiro, which is the succeeding version of our previous Kotaro.**

I. INTRODUCTION

Humanoid robots are expected to live with humans for assisting humans' daily tasks. Safety and versatility will be a key feature for such applications. Currently normal humanoid robots are not suitable for working in our daily environment. Lack of safety and versatility is a reason; the hard and heavy body can hurt human or surrounding objects, and conventional humanoid robots can do very few limited tasks compared with what a human is doing in the daily life. We have been studying on musculoskeletal humanoid robots [1], consulting human's body structure such as musculoskeletal structure and muscle-tendon driving system. At an exhibition called 'Prototype Robot Exhibition' at the EXPO'05 held in Japan, we had developed a super multiple DOF variable flexible spine musculoskeletal humanoid Kotaro [2], [3](Fig.2 and had shown an approach for achieving softness, naturalness and versatility.

This paper introduces our latest project of musculoskeletal humanoid "Kojiro". In the previous project of Kotaro, we have shown various proposals. The shoulder structure consisting of human-mimetic bladebone and collarbone has potential for wide movable range [4]. By adding rounded shape muscle units, a muscle-driven robot can be reinforced even after the design phase [5]. The three-dimensional angle sensors for spherical joints using mobile phone cameras [6] help estimating 3D rotational posture of ball-and-socket joints. The bandage type tactile sensors and fleshy tactile sensors realized natural interaction with children. Kotaro could become able to pedal a cycle by self repeated training in the real world [7]. We have also realized standing by reinforcing muscles [8].

One of the problems of Kotaro was comparatively low limitation of actuators' performance, and repeatability and dependability of sensors. The dependability of sensors are very essential for complex body robot like Kotaro which needs learning or self-training for acquiring various motions based on sensory information. Almost all of actions needs some

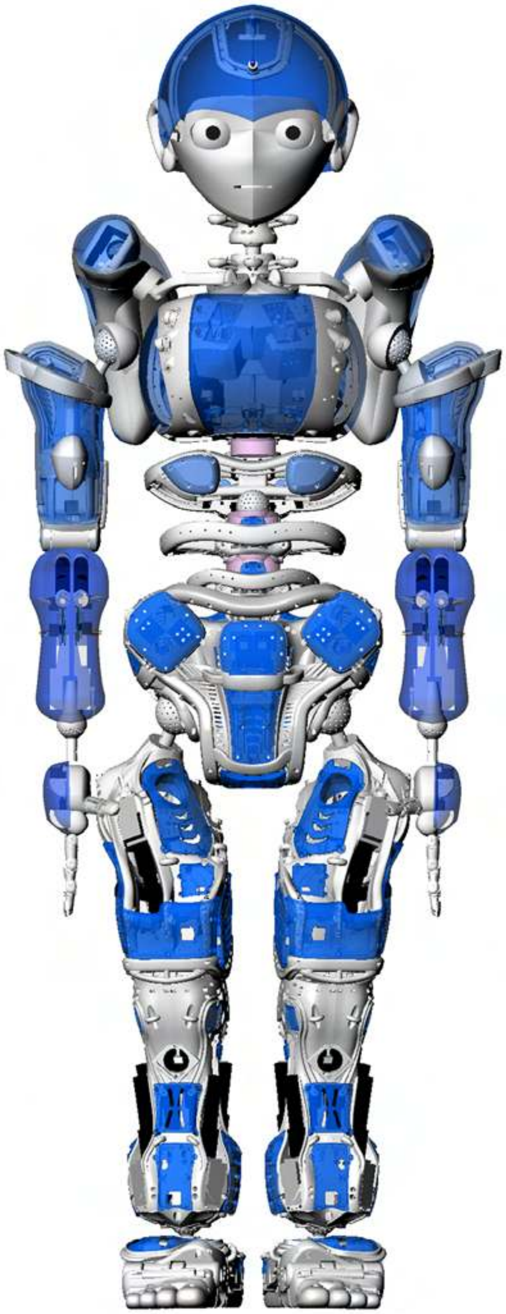

Fig. 1. A CAD image of Kojiro

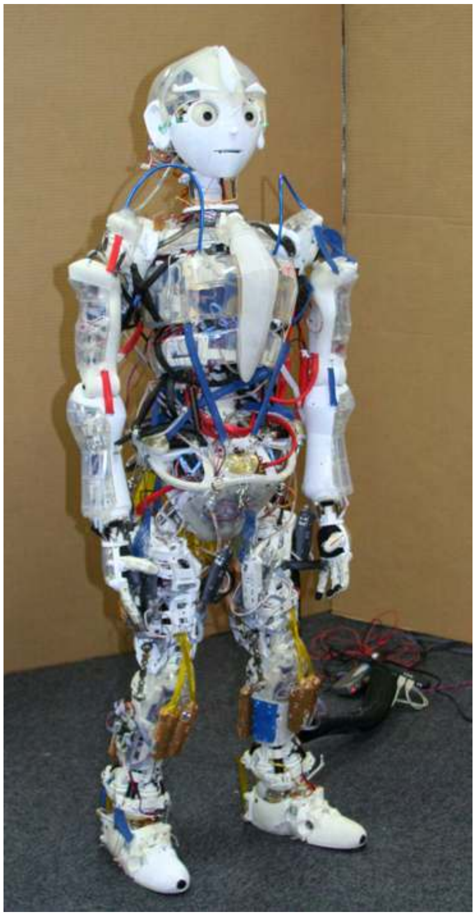

Fig. 2. Kotaro: our previous musculoskeletal humanoid

sensory information. The problem of actuator performance comes from the limitations of commercial electric motors. The newly released series of maxon brushless motors are very high power/weight compared with previous DC motors by maxon. We decided to incorporate the brushless motor by developing a very small amplification circuit board.

We aim at realizing significant improvement of physical performance of musculoskeletal humanoid robots, and also enhancement of sensor repeatability, robustness, and dependability. We have been trying to solve problems which became clear through the demonstrations and experiments. We have been developing a new musculoskeletal humanoid Kojiro as the next version of Kotaro, solving the above mentioned problems including performance of actuators and sensors. This paper presents the advancement from Kotaro to Kojiro, the concept and outline of Kojiro design, and what we are planning to clarify by Kojiro experimentally.

There are few works on musculoskeletal flexible spine humanoids. Or's work of a flexible spine humanoid [9] focuses on the flexible spine of a human, which shows us that at present human's body is far more sophisticated than robots. He also developed a prototype of a flexible spine humanoid, though it is not muscle-driven.

II. MUSCULOSKELETAL HUMANOID —CONTINUITY FROM KOTARO—

As well as preserving continuity from the Kotaro project, the targets of Kojiro project include realization of various actions in the real world by greatly improving physical performance, accurate and repeatable acquisition of the self-body state by greatly improving sensing performance, and the robustness of the full system by redundancy and noise tolerance. Fig.1 shows a CAD image of Kojiro. At present, the pelvis, both legs, lower part of the spine, head, and neck are completed [10], [11] (Fig.4 and Fig.5), and the design of the chest, shoulders, arms and hands are at the final stage. Kojiro's wholebody will be completed around this September.

Our Kojiro project aims at showing musculoskeletal humanoids' advantages which were what the Kotaro project also aimed at. As well as those, the Kojiro project aims at getting over Kotaro's weaknesses. Following items are the aims of the Kotaro project as research of a musculoskeletal humanoid.

A. Multiple Degrees of Freedom

Richness of DOF brings rich variety of applicable tasks and high adaptability to various environments. A musculoskeletal structure is suitable for increasing degrees of freedom, because some muscles can work cooperatively while each actuator of a serial-articulated robot structure cannot work cooperatively.

B. Multiple Joint Spine

Spine is the most polyarticular part in a human body. A human unconsciously uses the spine effectively in many motions and the movements of the spine greatly contribute to the adaptability to the environment and adjustability of the postures.

C. Multiple Sensors

Kotaro has various kinds of many sensors. Each motor, which pulls the muscle wire, has a rotary encoder, a tension sensor, a current sensing circuit, and a temperature sensor. Mobile phone joint-angle sensors [6] are embedded in some of the spherical joints. Two six-axis force sensor are embedded in both ankles. Three gyro sensors and a three-axis accelerometer are mounted in the head. Kotaro also has stereo vision and stereo audition. Kotaro has two types of tactile sensors. Kojiro will be equipped with these sensors as well.

D. Mechanical Softness

Many of conventional humanoids' bodies are rigid and collision with a human is not recommended. The movements of them are also rigid compared with humans' or animals'. We have been challenging to drastically change the structures of whole body robots; we have developed several whole body robots which have mechanical softness.

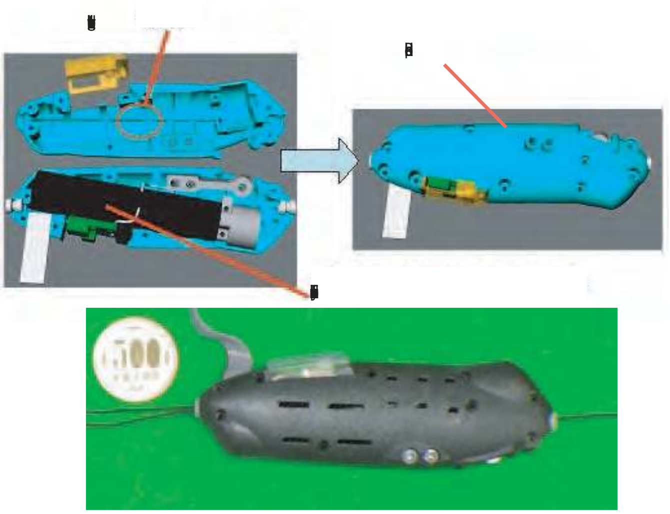

Fig. 3. Kotaro's muscle unit

E. Elastic Elements between Joints

There are elastic and viscous elements between vertebrae of human's spine and they function shock absorbing, etc. In case of musculoskeletal humanoids, these elements generate a force to return to the initial posture This force is normally against the gravity and helps actuators. In addition, the elasticity and viscosity makes the posture of serial joints smooth, and increases stability of a posture.

F. Adjustable Joint Stiffness

Since wire-actuators have tension sensors, the tensions of tendons can be controlled based on the tension sensor's feedback. By the force control of wires, the stiffness of joints can be controlled. There are cases in which stiffness is needed or softness is needed.

G. Reinforceable Muscles

By 'reinforceable muscles,' we mean it is easily to add or remove muscles, or rearrange muscle-attaching positions. Muscles of humans and animals will strengthen as growing up, while it is quite difficult to increase, decrease or change the actuators of conventional humanoid robots. It will be very difficult to decide the actuators' arrangement and power distribution of humanoids at the design phase because the variety of expected tasks is very diverse. The concept of reinforceable muscles [12] enables the modification of the balance of actuators according to the required tasks. We have designed a muscle unit (Fig.3). Muscle attached positions (both ends) can be freely modified. Each muscle unit consists of a DC motor with gearhead, a pulley, a tension sensor using strain gauges, a thermometer, a sensor-amplifier circuit board (18[mm]×12[mm]), and a rounded-shape outer shell.

H. Impressions Given to a Human

Since the skeletal structure and joint arrangement resembles a human's and the physical softness contributes to the litheness, we can expect this kind of musculoskeletal humanoids more natural movements which are closer to human's movements.

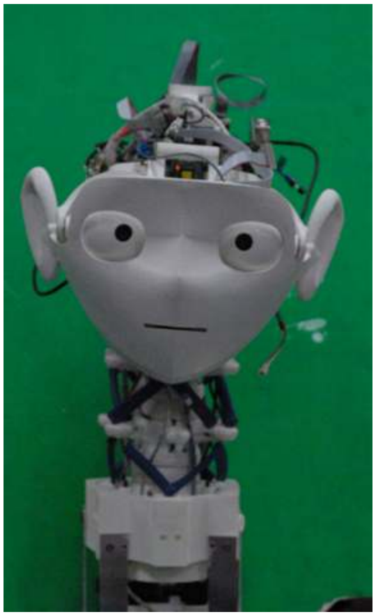

Fig. 5. Current status of Kojiro head

III. FROM KOTARO TO KOJIRO

A. Significant Improvement of the Actuator Performance

An aim of the Kojiro project is significant improvement of the moving performance. By improving the performance significantly, we aspire the realization of various motions including athletic motions in the real world by the musculoskeletal humanoid. Maxon motor has released a new brushless motor after the development of Kotaro, which was our previous musculoskeletal humanoid developed for the EXPO'05. The new brushless motor called EC16 40W is a very small, lightweight, and high-power motor: the diameter is 16[mm], the length including the output shaft is 66.4[mm], and the weight is 58[g]. Compared with the 4.5W DC motor used in Kotaro, the nominal output power is as about nine times high as Kotaro's 4.5W DC, while the size and weight is almost the same.

To introduce the new high-power motor, we have developed a very small brushless motor driver circuit board (Fig.6). The size of the board is 46[mm]×36[mm]×7.5[mm]. The board can drive two brushless motors. The maximum input voltage in the power line is 48[V], the maximum continuous output current per motor is 6[A]. This board can generate 20[A] for 15[s]. There are a microcontroller and a CPLD on the board, and it can communicate with a remote PC via the USB. The protocol in the USB line is the same as the protocol used in Kotaro's circuit boards and we can use the same software system for controlling Kojiro.

In order to extract potential higher power from the brushless motors, we have developed a method of active temperature

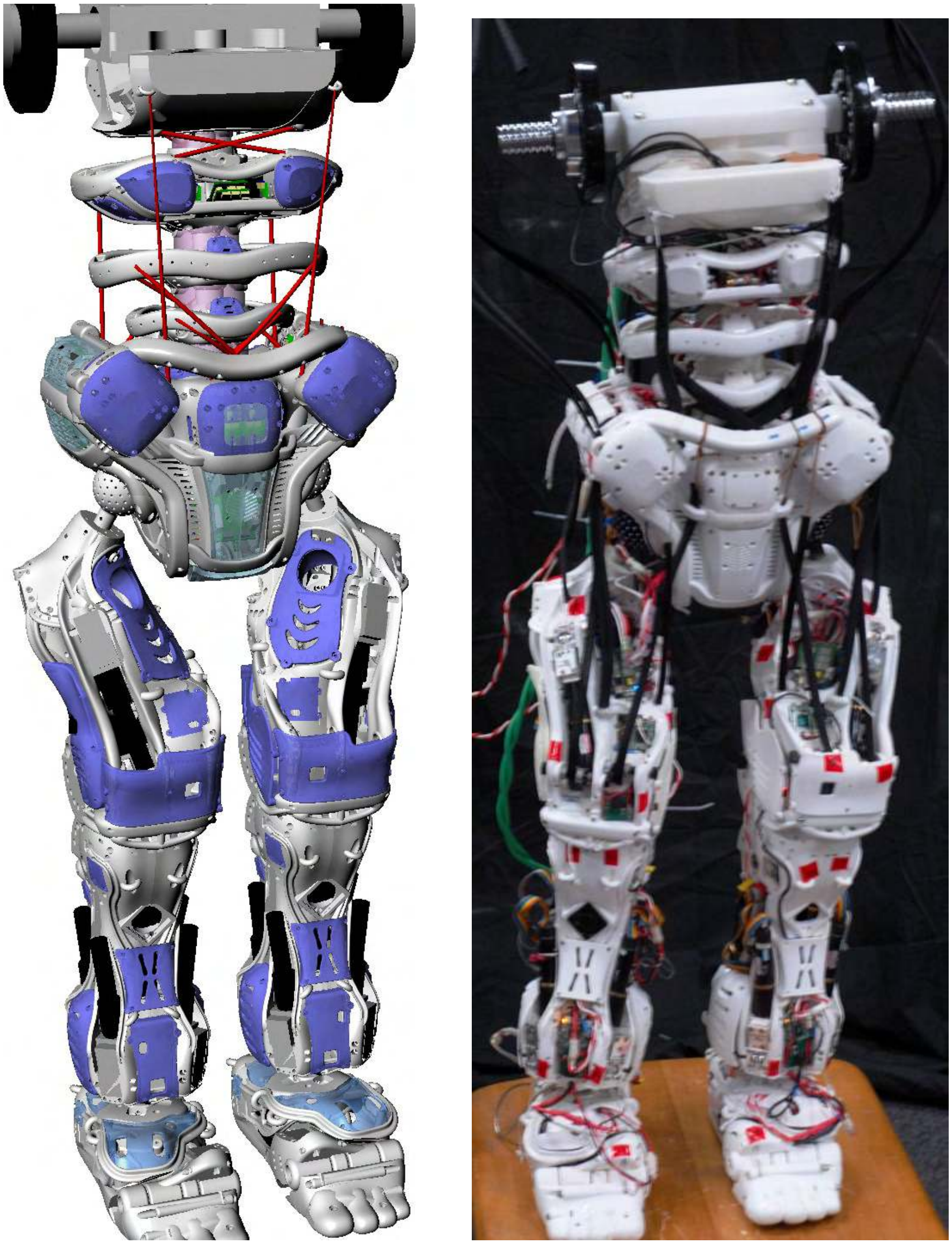

Fig. 4. Current status of Kojiro (left: CAD, right:real photo)

control. The method safely improve the output of motors. The active temperature control is achieved by using the temperature sensors attached to the motors and estimation of the inner temperature from the history of current consumption and the temperature information measured by the sensors. The developed system automatically adjusts the output current restriction according to the estimated temperature inside the motor. By this system, the motor can generate far more power than the nominal power for a certain small time period. This feature is very effective for humanoid robots, which does not necessarily need to generate much power constantly but rather need to generate instantaneous high power. At the design of Kojiro, we have set fans in the structure by considering the flow of the air inside bones.

To check the feasibility of high performance athletic motions, we have performed some experiments using the current Kojiro's body. At present, a weight can be attached to the chest of Kojiro and we can set the weight which is the same weight as the planned weight of the upper body of future Kojiro. Fig.7 shows some motions of Kojiro, to which the 12.5[kg]

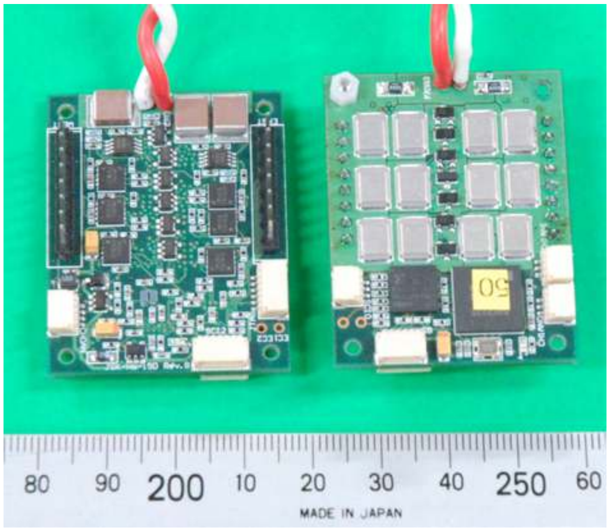

Fig. 6. The brushless motor driver circuit board we newly developed

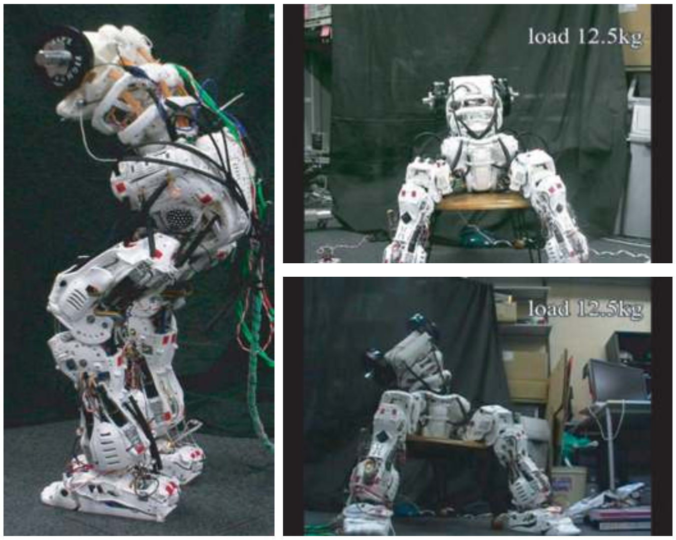

Fig. 7. Some motions of current Kojiro

weight is attached. We have got good performances through the experiments.

B. Improvement of Perception Performance

A musculoskeletal humanoid that has mechanical flexibility is, in general, a system whose nonlinearity is strong and it is hard to model precisely. To control such a system, a kind of learning method would be effective. Learning characteristics of the body and/or control algorithm would be necessary. In case of Kotaro, the repeatability and accuracy of the joint-posture sensors and tension sensors were not high, and it was difficult to obtain the accurate status of the body. The tension sensor used strain gauges for measuring the tension. There are temperature drift and differences by the individual sensors. We had to contrive ways to use the sensors for learning; we prepared an outer sensor instead of the embedded inner sensor, or an experiment was done in the area in which sensor repeatability is high.

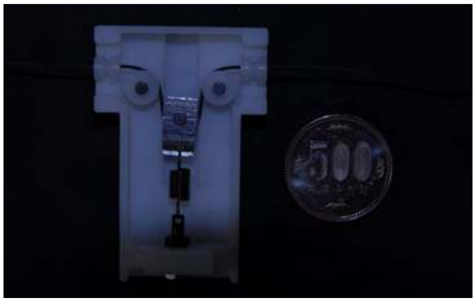

Fig. 8. A compact nonlinear spring unit we designed

In the Kojiro project, we have improved the perception performance of sensors. We have attached joint-angle sensors to all Kojiro's joints including rotational knee joints. As for the eyeballs and bladebones, it was difficult in Kotaro to measure precise posture of these elements. In Kojiro's case, we have used rotary encoders to obtain the precise postures of the eyeballs, bladebones, and collarbones. Though we did some experiments of learning using Kotaro [7], we will be able to tackle the learning issues more deeply by Kojiro.

C. New Bladebone-Collarbone Structure

Kotaro's human-mimetic shoulder structure consisting of a bladebone and a collarbone was a challenge for wide movable range and making space inside the shoulder [4], [13]. A shoulder of Kotaro has three ball-and-socket joints: the joint between the chest and the collarbone, the joint between the collarbone and the bladebone, and the joint between the bladebone and the upper arm. Though each of these spherical joints has a joint-angle sensor using mobile phone camera [6], it was difficult to calculate the accurate position and orientation of the end of the hand. Although Kojiro's shoulder also consists of a collarbone and a bladebone, the joints at both ends of the collarbone are rotational joints and rotary encoders are installed. Only the shoulder joint which is between the bladebone and the upper arm is a spherical joint and the joint-angle is measured by the mobile-phone camera sensor. By this design, we can obtain more precise posture of the bladebone seen from the chest, and we can obtain more precise position and orientation of the hand.

D. Nonlinear Spring Element

Generally, a wire-driven robot can modify the mechanical stiffness of joints by serially inserting nonlinear spring elements into the wire [14]. The larger the tension increases, the more rigid nonlinear spring becomes. The structure of a nonlinear spring tends to become complicated and large. We have designed a new compact nonlinear spring unit (Fig.8) which can embed into a forearm of a normal-size humanoid and are planning to insert the units into various muscle-tendons of Kojiro.

IV. CONCLUSION

This paper has presented the project of Kojiro, a musculoskeletal humanoid robot. Kojiro is positioned as the next version of previous humanoid Kotaro which was developed for the EXPO'05. The highlight of Kotaro was realization of standing itself by reinforcing muscles using improved muscle units. We continuously made mechanical improvements, while studying how to find and create the mechanism and algorithm of control and processing of sensory-motor coordination, in order to grow the robot. Advancing and development of musculoskeletal humanoids research may track the developing process of a human baby.

We suppose balancing using sensor feedback will be realized utilizing the ankles' 6-axis force sensors, followed by research towards walking. Other future studies include the mechanism of autonomous discovery of environmental restriction from information by multi-modal many sensors, realization of motions by controlling tensions of muscles in spite of lengths, and so on. From mid-term to long-term view, investigations on using artificial muscles such as pneumatic or electro-active polymer actuators, studies on joint structure with articular capsule like human's joints, soft flesh, energy source, etc. will be also issues. Our goal is to realize a humanoid that has as softness, many DOF, and adaptability as humans.

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