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A Reinforceable-Muscle Flexible-Spine Humanoid “Kenji”

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Abstract— **We have been studying about muscle-tendon spined humanoid robots for aiming a novel humanoid robot that has modifiable mechanical flexibility, safety and wide variety of postures. This paper describes a new concept of *reinforceable-muscle* humanoid and the development of a new musculo-skeletal humanoid robot named “Kenji” that is a prototype muscle-driven humanoid next to previous developed humanoid “Kenta”. Kenji has 140 actuators in total and numerous multi-modal sensors. This paper also presents some experiments that show the feasibility of the robot.**

Index Terms— **Musculo-skeletal humanoid, Reinforceable muscles, Redundancy, Flexibility**

I. INTRODUCTION

The structure of humanoid robots will be more complicated, be equipped with numerous actuators and sensors, and have mechanical softness, for doing activities in a human’s field such as home and for doing various practical tasks. We have been studying on muscle-tendon spined humanoid robots for aiming modifiable mechanical flexibility, safety and wide variety of postures. This paper discusses a concept of *reinforceable-muscle* and *flexible-spine* humanoid, and the development of a new musculo-skeletal humanoid robot named “Kenji” that is the prototype muscle-driven humanoid next to previous developed “Kenta” [1]–[3]. Reinforceable muscle means that we can easily add/remove muscles or rearrange muscle-attaching positions. Muscles of human and animals will strengthen as growing up, while it is quite difficult to modify, increase, decrease or rearrange the actuators of conventional humanoid robots. It will be very difficult to decide the arrangement of actuators of humanoids because of diversity of expected tasks. The concept of reinforceable muscles will enable to modify the balance of actuators by adding, removing or rearranging the actuators according to the tasks required to the robot. In our design of muscle units, the fixing positions of (both ends of) muscles can be freely modified. Using the units, we have designed and developed an endoskeletal lower body and multiple-DOF hands, and integrated into a new humanoid Kenji. As well as the concept, design, and implementation, this paper also presents some demonstration to show the possibilities of our concepts.

II. REINFORCEABLE-MUSCLE FLEXIBLE-SPINE HUMANOID

A. Humanoids in a Future

In future, humanoid robots are expected to work in humans’ life and do vast variety of tasks, such as washing, drying and tidying away dishes and clothes, cleaning rooms, making beds, and so on. To work in humans’ fields, the robots have to be absolutely safe, adaptable and applicable to the diversity of tasks, able to do natural motions, and so on. One possible direction of robot’s progress, we suppose, is a human-like body structure. An ideal is human’s body, which has variable flexibility, very redundant multiple degrees of freedom, and mechanically elastic high-power muscles. The variable flexibility provides safety and support structure, the very redundant multiple joints give really wide task availability, and human’s body can move far naturally compared with current robots. Getting closer to human’s body structure

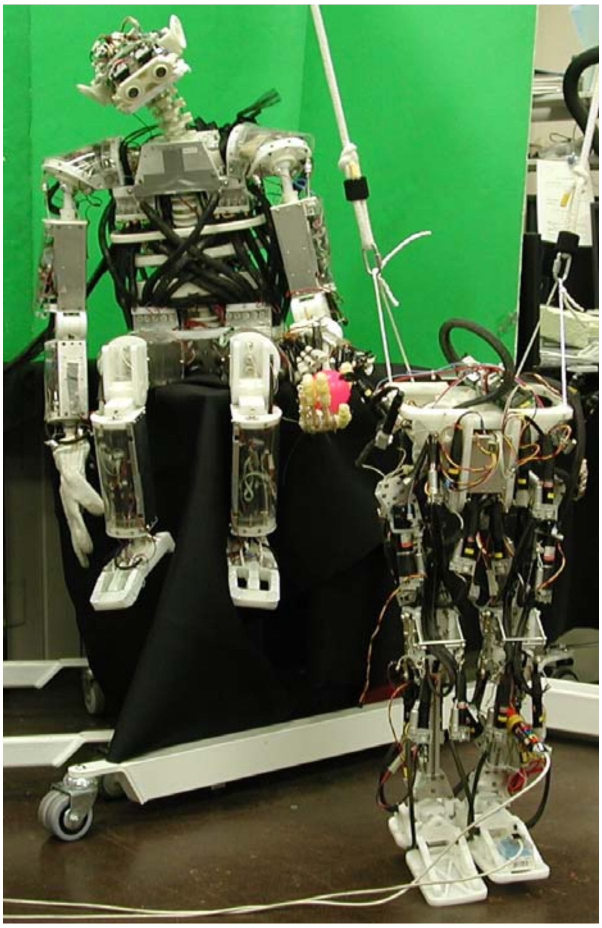

Fig. 1. The previous muscle-driven humanoid Kenta (left) and reinforceable-muscle humanoid-leg (right)

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could be a solution to the problem of humanoids' working in our daily lives. It would not be far from extraordinary that humanoids' body structure will be more complex and humanoids will have more sorts and numbers of sensors.

B. Muscle-Driven Flexible-Spine Humanoid

Almost all of the human-form robots ever developed were so rigid that there was a danger for human to be hurt. The research on flexible robots [4] or multi-joint-structure robots [5], [6] have not been applied to the torso of humanoids. On the other hand, though there have been some researches on embedding a movable mechanism in the torso (trunk) of human-form robot [7], these robots' torso can rotate around only one concentrated axis and they do not have any variable flexibility. We propose a robot which has variable flexible structure in the torso (spine) [8]. By embedding a soft spine into the torso, robots will have several characteristics. First, the degrees of freedom of torso increase. It means that the movable area of the robot or of the arms would be expanded. It also means that, by using the increased DOFs, motions of the robot can be more efficient compared to a rigid torso. The motions of the flexible spine robots could be nearer to natural (human-like) motions. Secondly, by the softness of the spine, the robot can absorb the shock, and it has a safety at the physical contact with a human or objects. Third one is variable flexibility. The spine of human-form robots has to support the upper body when needed. In another situation, the robot may have to adapt to the outer force put by human. When the robot needs to lift up a heavy object from the floor, the spine should be comparatively hard. The variability of the flexibility is very important.

Embedding a mechanical flexible structure into a robot body has been a research issue and there have been various studies and trials [4], [9]–[13]. Modifiability of softness is also important [8], [12]. For increasing the degrees of freedom, and having redundancy and modifiable flexibility, muscle-driven mechanism is effective. In muscle-driven systems, joint structures depend little on actuation systems. In case of a robot consisting of motor-driven rotational joints, increasing actuators or redundancy is not easy and to have variability of mechanical flexibility needs additional structures [12]. A robot system in which tension-controllable muscles drive a skeletal structure with passive joint is easy to have multiple redundant degrees of freedom using ball-and-socket joints and easy to have modifiable mechanical flexibility using muscles whose tensions can be controlled [14].

We have been studying on muscle-driven robots with flexible spines [1], [14]. Spine is the part that has most degrees of freedom in a human body. The spine of vertebrate animals has 24 joints in total from the hip to the neck, and each joint has 5 or 6 degrees of freedom. We use our spines in almost all of our motions unconsciously. Most motion captured data from human's motion have information on the movements of the spine. It implies that the movements of the spine play a part in human's natural motions. We have developed flexible spine robots and performed some demonstrations showing the effect of the spine [2], [8].

C. Reinforceable Muscle Humanoid

Humanoid robots are expected to do very wide variety of tasks in humans' life. It will be quite difficult to decide the arrangement of actuators and degrees of freedom at the design phase; it will be even almost impossible to decide the adequate arrangement for all kinds of expected works. Equipping robot with strong actuators and/or all kinds of DOF is not a good way; it would result in a very heavy robot. Required arrangements of actuators and joints will depend on the required tasks and situations. It is a trade-off between optimization of the structure and diversity of task availability. There may be some cases in which the decision can be made only after experiencing some motion in the real world.

We propose a concept of rearrangeable muscle humanoid. If the arrangement and amount of actuators is easily modifiable, the sufficient and efficient arrangement of DOFs and actuators can be decided according to the situation in which the robot works. The situation can differ even after being installed, especially in human's environment.

Joint-motor systems and exoskeletal structure of normal humanoid robots (e.g. [15]–[17]) is not suitable for the rearrangement. In joint-motor systems, in which each joint has one degree of freedom and actuated by one motor, adding or removing a DOF (joint and motor) needs designing and producing of mechanical structure again. In a rigid exoskeletal robot, it is difficult to replace the motor whose size or shape is different. A solution to the problem is an endoskeletal structure actuated by a parallel muscle-tendon system. Ball-and-socket joints which have three degrees of freedom would help the reconfigurability, for power property of this kind of joint can be modifiable only by changing the arrangement of muscles that actuate the joint. It can also be said that a ball-and-socket joint realizes a simple and compact mechanical structure of three degrees of freedom, compared with serial three rotational joints. Endoskeletal structure provides a space for muscle rearrangement; a region where muscles are reinforced would become thicker, but it is same as human's case. The system allow to have also multiarticular muscles and cooperative muscles [18] like human and animal.

Comparison between endoskeletal structure and exoskeletal structure is as follows:

- Endoskeletal structure is:
  - easy to increase/decrease muscles, and easy to modify attached positions of muscles
  - possible of arranging muscles imitating human
  - easy to modify the shape of cover or skin
  - difficult to implement cover or skin
- Exoskeletal structure is:
  - easy to attach skin function (e.g. tactile sensor)
  - difficult to re-arrange, add, or remove muscles
  - different from human structure
  - difficult to change the shape design

D. Paradigm Shift of Design and Control of Mechanical Systems

A robot that has many actuators and sensors, and variable flexibility tends to become a very complex and inconstant system. While design and control of a mechanical systems have been focusing on rigidity and accuracy, this type of robots may need a different way of thinking about control and design. Human's body structure does not have such rigidity as current humanoid robots have. We do not move arms so precisely as manipulators do. The system of human allows the uncertainty compared with mechanical systems, manages complex non-linear inputs and outputs, and is adaptable even to the changes of the body structure; we can adapt to growing up and tiredness.

One of our aim is to know how to create such a system like human's in a so-called constructive approach. We are trying to build a system that can acquire the relation between the actuator operation and resulting sensory information from the real sensors [19]. If a system of that kind is realized, it would be a big breakthrough in the design and control of mechanical systems; we would not need to make machine not so accurately but just need to attach appropriate sensors and the system would learn by itself how to manage the mechanical structure as humans do.

III. THE DEVELOPMENT OF THE INTEGRATED MUSCULO-SKELETAL HUMANOID KENJI

Based on the concept discussed in Section **II**, we have developed human mimetic reinforceable-muscle hands (Fig.4). We have also developed reinforceable-muscle humanoid legs(Fig.9). We have, finally, integrated these hands and legs with the revised flexible-spine and the neck and head of Kenta, into a new muscle-driven flexible-spine humanoid, Kenji.

A. The Design of Muscle Unit

To implement the reinforceable muscle humanoid, we have designed and developed muscle units (Fig.3 and Fig.5). The upper figure of Fig.5 shows the mechanical structure of the muscle units. A unit consists of an electric motor with reduction gearhead, a length sensor (the rotary encoder attached to the motor), a tension sensor, and two pulleies. Two wires are connected to a unit; one wire is connected to the tension sensor and the other is wound up by the pulley fixed to the motor's spindle through the other pulley which changes the direction of the wire. The latter pulley in the slit is not seen in the upper figure of Fig.5. In previous muscle-driven or tendon-driven systems, the motor and pulley to pull a muscle or tendon was placed at one end of the wire. In case of the designed pulley unit, the motor is placed at the middle of the muscle wire. Therefore the fixing positions of the both ends of a muscle can be freely determined. Thus easy rearrangeability of muscles is realized.

The length of the coil spring in the cylinder changes according to the tension changes of the muscle. By measuring the distance between the piston and the bottom of the cylinder, the tension is detected. The measurement of the distance is done by a photo interrupter which uses infrared LED and infrared photo transistor. The lower pictures of Fig.5 shows two kinds of the developed united muscles using 4.5[W] and 20[W] DC motor[1].

Fig. 2. Bones of the right hand

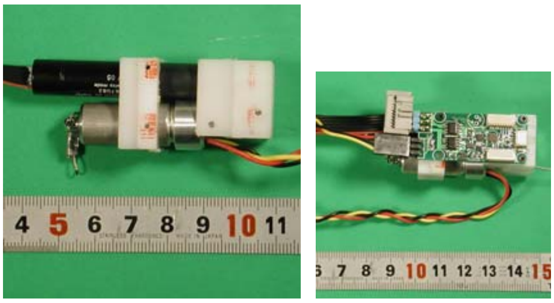

Fig. 3. Muscle units for hands. The circuit board in the right photo is a driving circuit.

B. Human mimetic reinforceable-muscle hands

Fig.2 shows the skeletal structure of the new hand. The structure is inspired from that of human's hands. The bones of wrist joint are similar to radius and ulna. The direction of the axis of the root joint of thumb is different from root-joint axes of the rest of fingers. The articular capsule of each joint is made from rubber tube (yellow objects in Fig.2).

Fig. 4. A reinforceable muscle hand for Kenji

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[1] MAXON, RE16 and RE25

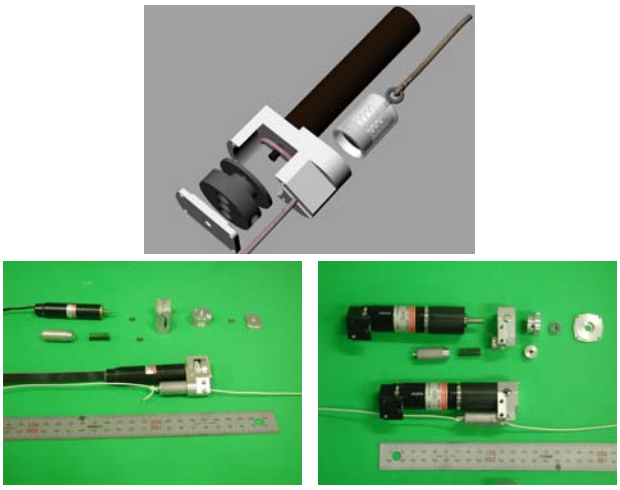

Fig. 5. Muscle units for legs. The upper figure shows the structure of a unit, the left photo shows a smaller unit using 4.5W motor, and the right photo shows a larger unit using 20W motor.

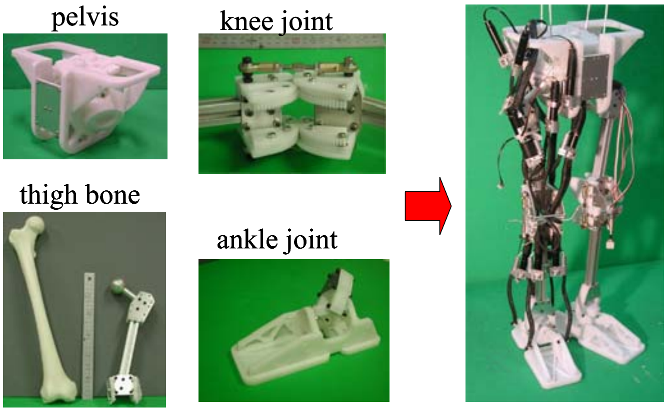

Fig. 6. The endoskeletal structure of the legs

Fig.3 shows muscle units for hands. The left photo in Fig.3 shows a unit without a driving circuit. The right one shows a unit to which the motor-driving circuit board is attached. There are a motor-driving circuit and very small (3[mm]×3[mm], 9pins package) microcontroller[2] on the board. The microcontroller chip has PWM function, digital/analog I/O, and communication channels; we can assign a certain function to each pin. Each unit also has a tension sensor based on photo-interrupter [1], [20] .

Fig.4 shows the whole hand which is the integration of the bone structures, articular capsules, tendons (thin wires), rubber ligaments, and muscle units with microcontroller and motor-driver circuit. This hand can replace the previous hand of Kenta, seen in Fig.4.

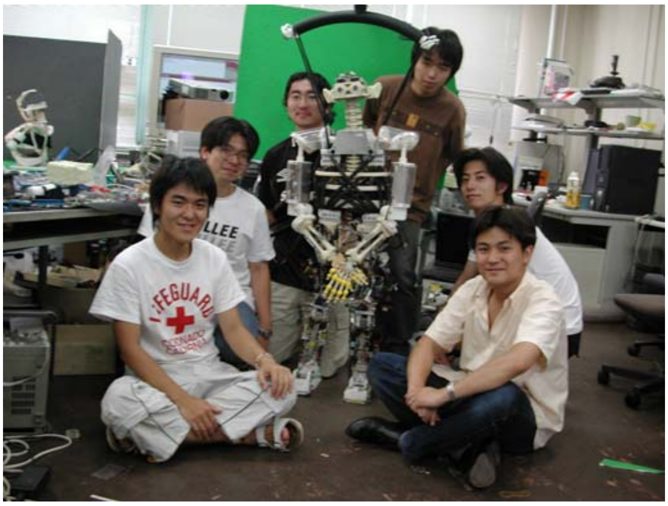

Fig. 7. Newborn Kenji

TABLE I
THE SPECIFICATIONS OF KENJI

category	type	quantity
	weight	21.0–24.0kg
	height	123cm
DOF	spine	$3 \times 10 = 30$
	neck	$3 \times 5 = 15$
	legs	$6 \times 2 = 12$
	arms	$10 \times 2 = 20$
	hands	$25 \times 2 = 50$
	head	2
actuators	DC motor	96–150
	RC servo motor	2
sensors	tension sensor	94–132
	rotary encoder	94–138
	current sensor	94–138
	3-axis accelerometer	8
	gyroscope	3
	tactile sensor	0–62
	CCD color camera	2
microprocessors	distributed controller	32–50
	gateway	4
host computer	CPU	8
	Memory	2GB

C. *Human mimetic reinforceable-muscle legs*

Basic design of the mechanical structure was presented in IROS2004 [21]. Fig.5 shows the structure of rearrangeable muscle units for legs, which use 4.5W motor and 20W motor. Fig.6 shows the endoskeletal structure of the legs. Each leg has six degrees of freedom; the crotch joint has three, the knee has one, and the ankle has two. 12 muscle units are initially installed and we can easily add extra muscle units or modify the arrangements; i.e. the attaching points of the both ends of units can be easily modified. Figure 8 shows a demonstration of changing the arrangement of muscles.

D. *Integration of the new hands and legs into previous Kenta*

Fig.7 shows the newly integrated reinforceable-muscle flexible-spine humanoid Kenji. Table I indicates the speci-

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[2] Cygnal, C8051 F300

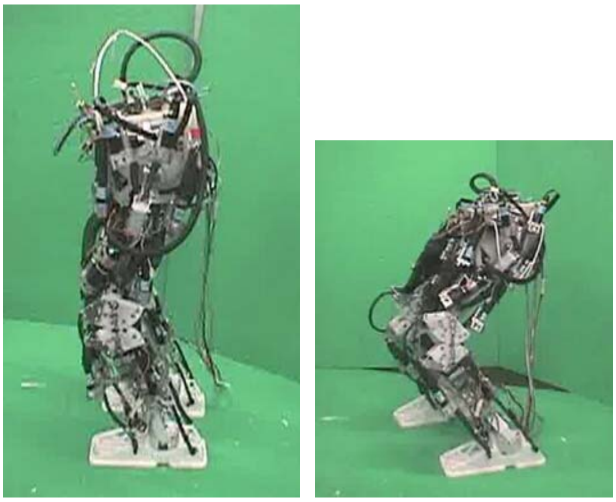

Fig. 8. Before adding muscles bending angle was smaller (left), and after adding muscles bending became deeper (right).

fications of Kenji. In the table, there are some quantities that show the range of value; e.g. the number of DC motors is from minimum of 96 to the maximum of 150. Based on our concept, the robot is able to have comparatively wide variety of system configuration even in the experiment phase, while in case of normal humanoid robots, the arrangement of actuators and sensors are decided at the design phase. We can even add extra controller circuit boards when some actuators or sensors are needed to be attached.

IV. EXPERIMENTS

In this section, some experiments using the developed real humanoid are presented.

A. Reinforcement of muscles

Figure 8 shows the experiments demonstrating the effectiveness of reinforceability of muscles. At the initial state (the left photo in Fig.8), the legs could stand up only from this bending angles. After adding two muscles around both knees for strengthening the knee-stretching force, it could stand up from deeper bending angles seen in the right photo of Fig.8.

Figure 9 shows the experiment of feasibility study where the developed lower legs is standing and supporting a 10[kg] load. In this experiment of Fig.9, four 20W motors installed are not used, and Kenta's upper body weighs about 12[kg].

B. Sensor-based marching behavior

In order to confirm the movability of the lower body, we tried a sensor-based marching behavior utilizing the force sensors on both foot. Figure 10 shows the marching experiment. The robot changes its posture according to the change of sensory information from force sensors on soles, which indicate the information on where is the center of the force.

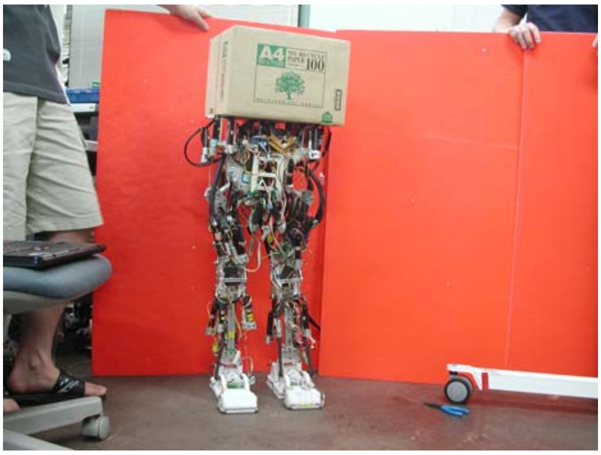

Fig. 9. A reinforceable-muscle legs for Kenji supports a 10kg object.

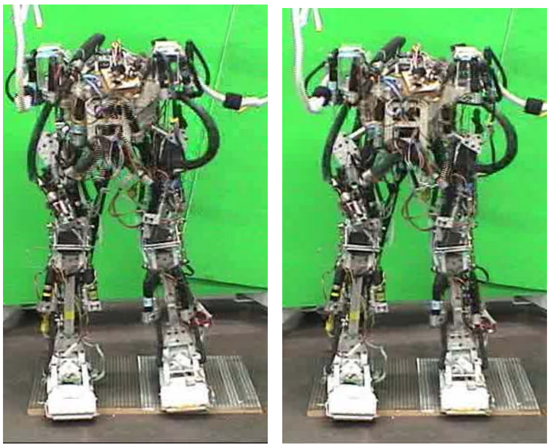

Fig. 10. Marching based on force sensors on both feet

C. Some trials for feasibility study by whole-body Kenji

Figure 11 shows an experiment in which Kenji is trying to do a gymnastic horizontal high bar using the flexible spine and legs.

Figure 12 shows an experiment in which Kenji is trying to do a standing riding of a cycle. When riding a cycle in standing condition, a human also fully uses the various sensory information. Kenji has sufficient degrees of freedom and sufficient number of sensors. The problem now is how to utilize them to realize the complex behavior.

V. CONCLUDING REMARKS

This paper has presented a concept of *flexible-spine* and *reinforceable muscle* humanoid, and development and integration of a novel musculo-skeletal humanoid robot named Kenji based on the proposed concepts. This paper also presents some experiments demonstrating the feasibility of the humanoid. Rearrangeability of actuators, which can be compared to animal's growability, is realized by the muscle units.

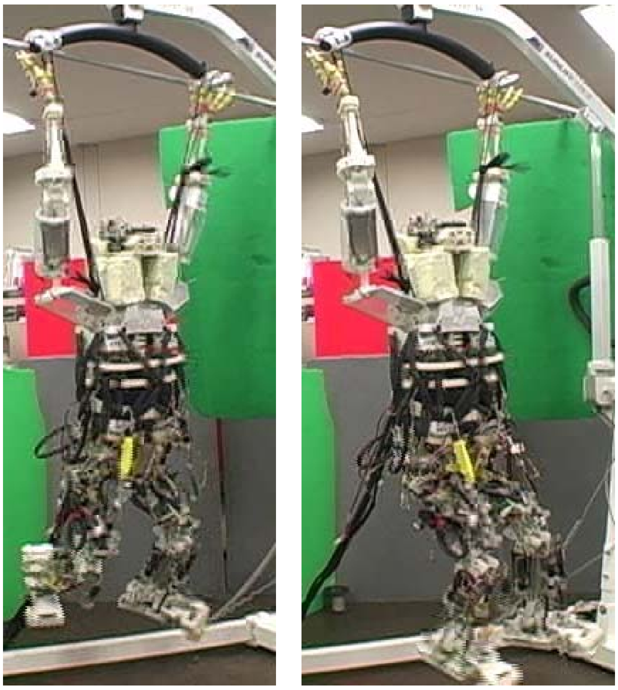

Fig. 11. Kenji trying a gymnastic horizontal high bar

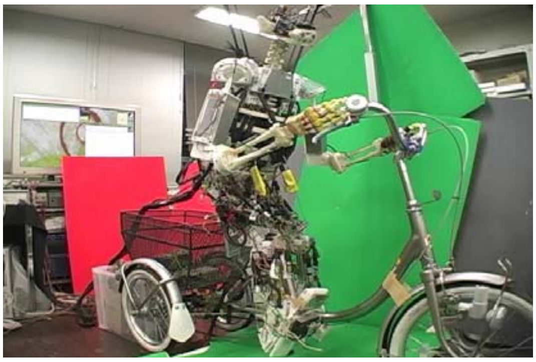

Fig. 12. Kenji trying a standing riding

Problems to be solved include acquiring the body information (i.e. relationship between the actuator operation and the resulting sensory information changes), methods to generate various sensor-based behaviors in conjunction with some learning methods, adaptability to the changes of actuators and sensors, and so on.

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