Building Spined Muscle-Tendon Humanoid

Masayuki Inaba, Ikuo Mizuuchi, Ryosuke Tajima, Tomoaki Yoshikai, Daisuke Sato, Koichi Nagashima, and Hirochika Inoue

Department of Mechano-Informatics, The University of Tokyo,
7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan

Abstract. Human can perform variety of limber whole-body motions using numerous muscles and huge number of various sensors. The human brain has all the connections to the sensors and muscles, and learn how to manage them for whole-body motions. In this research, we have aimed to build a complex body with physically massive parallel sensor-motor systems to enter the next stage for studying humanoid brain systems. It is designed to have a flexible spined torso and a whole-body with fully muscle-tendon driven systems. In this paper the design and implementation of the first model of the humanoid is described with some experiments.

1 Introduction

So far several whole-body humanoid robots have been developed (Hirai, 1997; Kato, Ohteru, Kobayashi, Shirai, Uchiyama, 1974; Nishiwaki, Sugihara, Kagami, Kanehiro, Inaba, Inoue, 2000). However, we often feel that the whole-body motions of the robots are restricted or unnatural because of the rigid torso. If we want to put a controllable flexibity in the torso, the mechanisms to drive it becomes a crucial point to be solved. Although there have been some studies on humanoid which has a movable torso (Yamaguchi, Inoue, Nishino, A.Takanishi, 1998), these researches concentrated on the movability of the torso at the hip, and there was no flexibility in the torso. One of the method to build the flexible torso is to use a spine like a vertebrate animal. The spine with multiple vertebra requires multiple actuators to be connected in each elements. One of the method to solve the problem is to control vertebra with muscle-tendon driven systems (Mizuuchi, Inaba, Inoue, 2001). However, the multiple muscle-tendon systems in a torso may give interference between each others and make hard to keep repeatability in various complex motions. This means the artificial robot that has a vertebrate type spine with muscle-tendon systems requires a capability to solve the problem like vertebrate animals do. One of our goals in this research is to provide a research platform to extend humanoid brain to manage this kind of complex bodies.

We have put several design policies for this research aim. The first is to adopt stiffness-controllable flexible torso with muscle-tendon systems. The second is to accept impact forces in a ball joint with a large surface contact. The third is to have new manufacturing systems for prototyping. Because many parts such as vertebrae uses free-formed surfaces, new method to handle free-formed surfaces are indispensable. The fourth is to keep inheritance of brain and mother software for development. The 'mother' software to generate the body models and basic program

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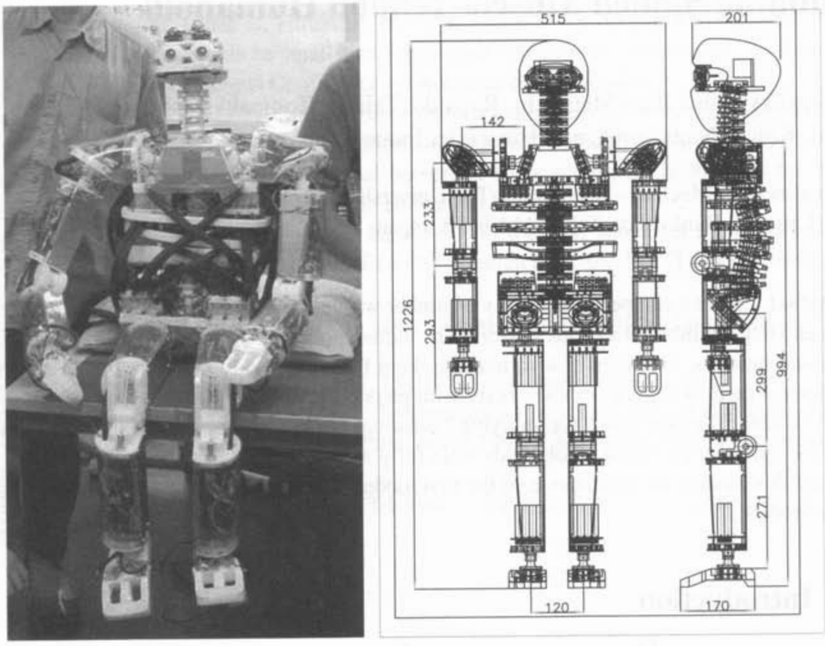


Fig. 1. Kenta, a spined muscle-tendon humanoid, Right: CAD design of Kenta

frames of controllers, which is used in the development of our humanoid series should be inherited in new design of humanoid.

2 Design of spined muscle-tendon humanoid "Kenta"

2.1 Design concept of the spined torso

By having a flexible spine whose flexibility is variable, robots will have several characteristics below.

The increase of DOF of the torso: A flexible spine has more degrees of freedom than a rigid torso. 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. (Figure 2.)

Multiple joint structure: There is some differences between multi-joint spine and single concentrated-joint spine (Yamaguchi et al., 1998). For example, in the motion to rise the upper body from the floor, a flexible spine robot can move each joint one by one from the neck joint to the hip joint. This procedure is more efficient than rising the upper body from floor using only hip or crotch joint. Furthermore, the motions of the flexible spine robots could be nearer to natural (human-like) motions.

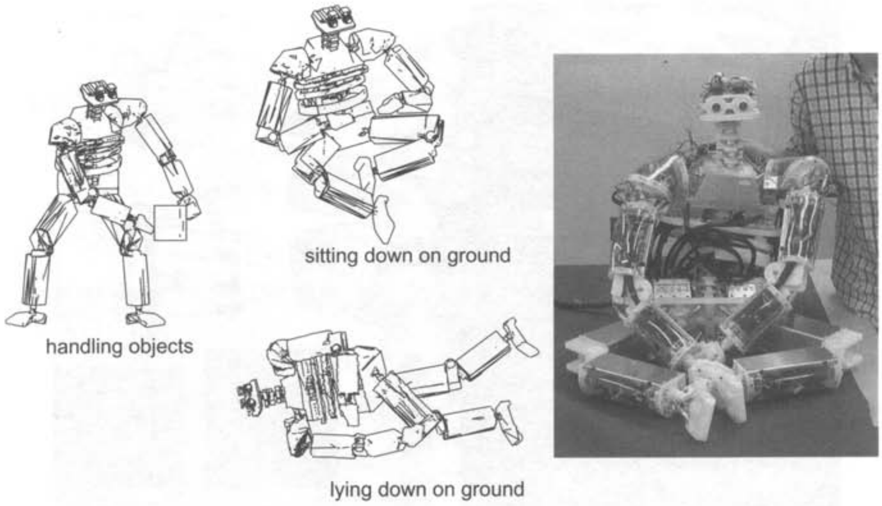


Fig. 2. 96 DOF whole body tendon-driven humanoid Kenta

Softness in material: 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.

Variable flexibility: For example, 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.

2.2 Mechanical structure of the torso

The design of the spine structure of Kenta follows the basic policy: based on the investigation of the structure and characteristics of human's spine, we try to follow the design and function as much as possible.

The vertebrae Kenta's spine consists of 9 vertebrae (2 types). The 9 vertebrae and hip and clavicle construct 10 ball-and-socket joints of the spine. Three ribs are attached to the three of the vertebrae. Between each two joints, there is a 'disk' made of silicone rubber, and there are also ligaments made of tension spring between the joints.

Normal human's spine has a curvature. By the curvature, the strength against the axial force is increased. The vertebrae of Kenta's spine have two kinds of inclination (each angle is 10 degree) (the left figure of the Fig. 3), to organize the curvature (Fig. 3). The movable range of roll-, pitch-, and yaw-rotation of each joint is approximately ± 10 degrees. But, the range of pitch-rotation is somewhat limited physically to about $-3 + 10$.

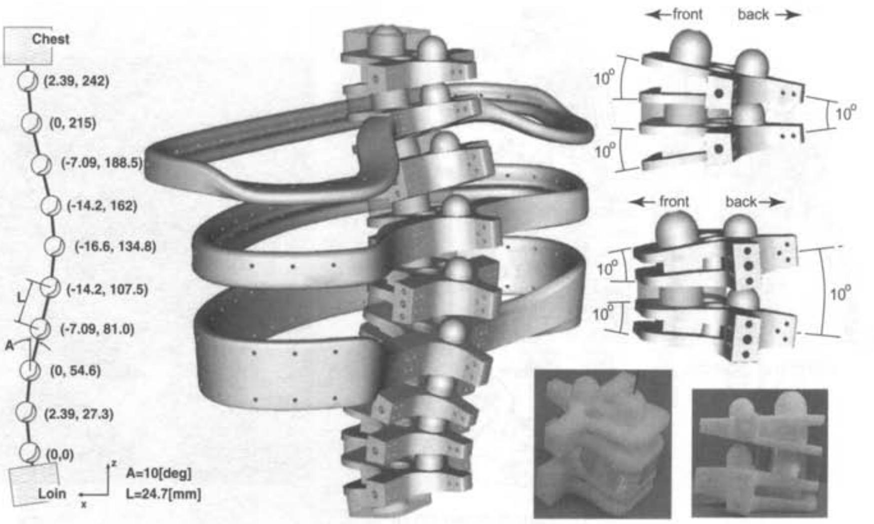


Fig. 3. Left: the link arrangement of the spine, Middle: CAD design of spine, Right: two kinds of inclination of vertebrae (an elastic part is between the two.)

The joint between vertebraes Each vertebra has a spherical protuberance on the top and a spherical dent on the bottom, as if there is a ball between the vertebrae (Fig. 3). The silicone rubber 'disk's are made using a plastic mold. The disks are put between the vertebrae in pressured condition and contribute to the flexibility of the spine. Each vertebra has two transverse processes (side protuberances) and a spinous process (back protuberances); process means a protuberance. Ligaments, which connects the processes, retain the structure and contribute to the flexibility as well. Expecting the function of ligaments, the vertebrae of Kenta's spine have the processes and there are the ligaments made of tension spring. The lower the position of the spring is, the higher the spring coefficient becomes. The small ball at the back of the top surface is to prevent the joint's over-bending.

The rib While human's ribs protect the internal organs, robots do not have any internal organs. The ribs of the robot's spine play another role as muscle-fixing parts. By fixing muscles to the ribs, the muscles are apart from the center of rotation of the trunk. This increases the force to change the posture of the spine, by the same tension of muscle; while the speed of changing the posture by the same actuator speed is decreased.

The actuators There are 40 motors to move the spine; twenty in the shoulder-block, and the other twenty in the hip-block. In the shoulder block, ten are in the right block, and the other ten are in the left block; in the hip block, ten in right and the other ten in left. The motors placed in inner side have power rather than speed,

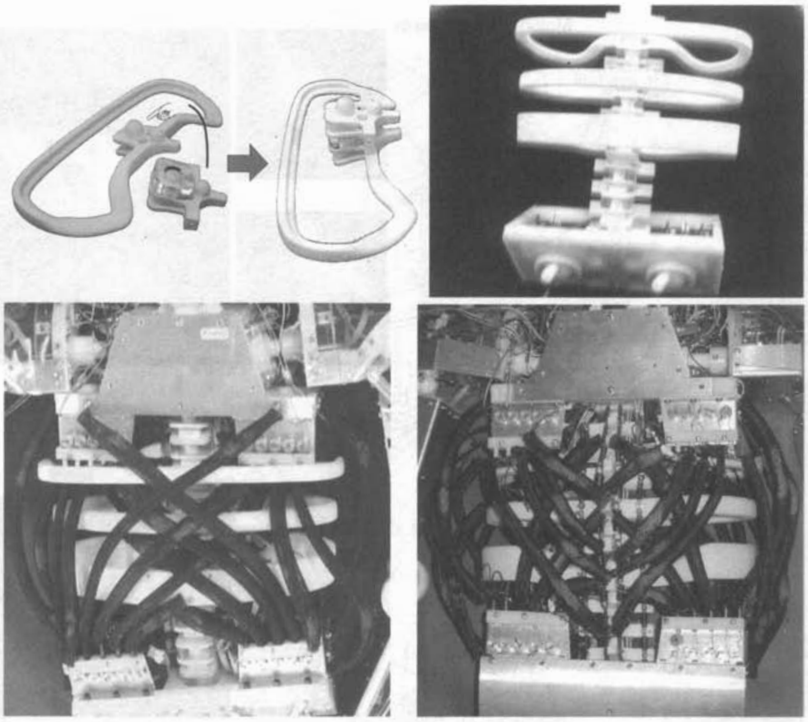


Fig. 4. The arrangement of muscles of Kenta's spine (left:front, right:back)

and the ones in outer side have speed rather than power. This is by the differences of gear ratios.

Figure 4 shows the arrangement of Kenta's muscles. At the front side, muscles are placed traversing the front surface, while at the back side, all muscles are fixed to the spinous processes (back protuberances) of the vertebrae. At the right and left sides, muscles traverse the surfaces.

2.3 The manufactureing methods

The complex shapes of Kenta's parts such as vertebrae, ribs, neck, eye-balls, etc. were designed on 3D-CAD softwares. At the manufacturing stages, the designed shapes were transfered all in the form of digital data. Parts were manufactured using NC machine tools, FDM-method (Fused Deposition Modeling), and SLS-method (Selective Laser Sintering). The left figure of the Fig. 4 shows a part of the one-body rib-vertebra. It is quite difficult for conventional CAD softwares to design this kind of complex shape, which can be designed using 3D modeling tools more easily.

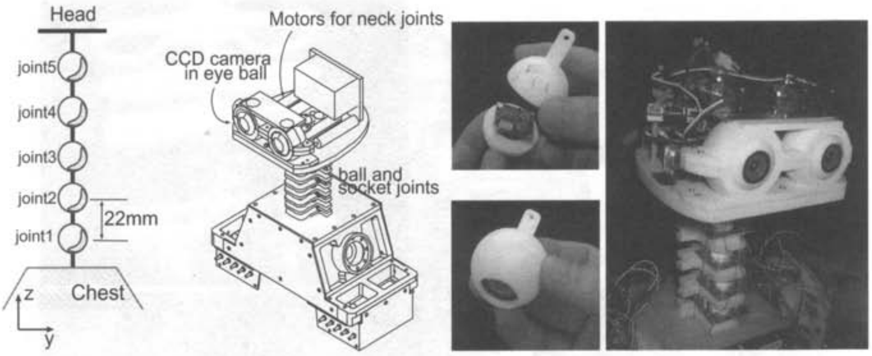


Fig. 5. The structure of Kenta's head and eye-balls

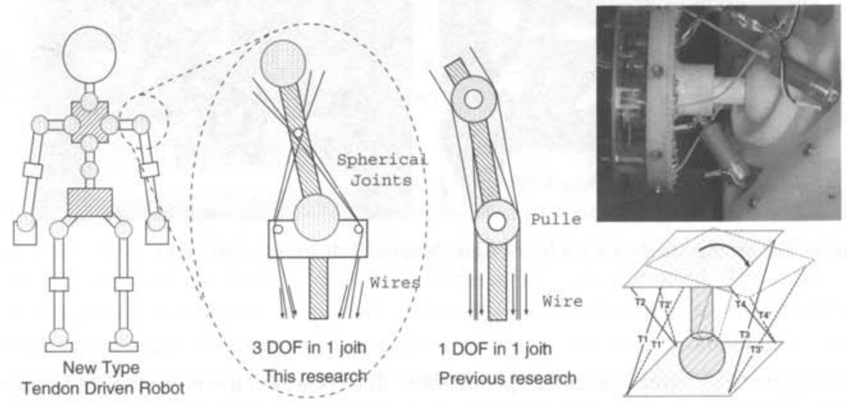


Fig. 6. Left: pulley-wire vs. non-pulley-wire, Right: ball-socket joint of crotch

2.4 The neck and head

The left of Fig. 5 shows the link arrangement of the Kenta's head. The structure of neck is like a small-scale version of the spine. The neck has five ball-and-socket joints like spine's vertebrae(the middle of the Fig. 5). Each joint consists of two small vertebrae and a silicone-rubber disk between the vertebrae. The elastic disks generates the force to restore to the natural posture when the neck is not in the natural posture. The neck structure is driven by six muscles. the posture of the structure is decided by the balance of muscle's tension, rubber-disks' force, and the external forces containing gravity. The structure of eyes are also ball-and-socket structures. Each eye-ball contains a CCD color camera. The eyes moves (pan and tilt) synchronously by two actuators.

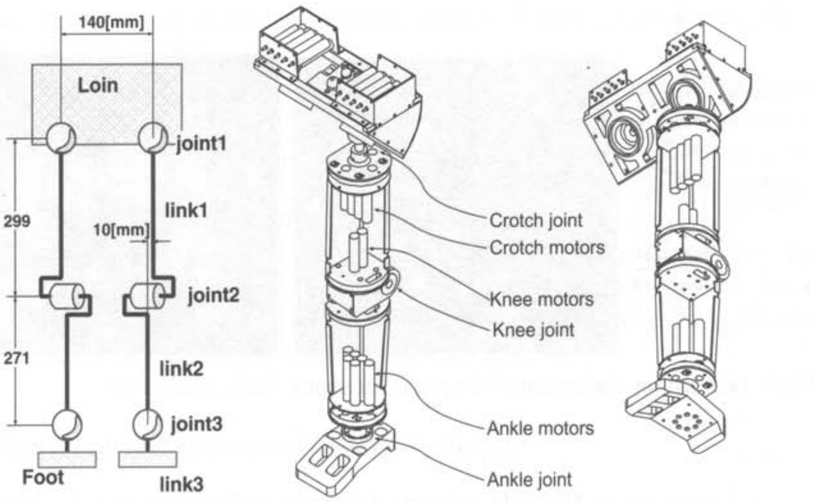


Fig. 7. Left:The DOF arrangement of Kenta's leg, Right: 3D view of Kenta's leg

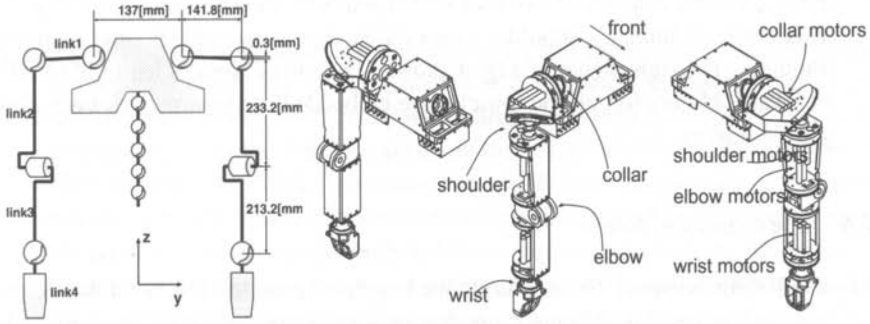


Fig. 8. Left: The DOF arrangement of Kenta's arm, Right: 3D view of Kenta's arm

2.5 The arms and legs

As a way to build a muscle-driven system, pulley-wire system and ball-socket joint system can be considered (Fig. 6). While pulley-wire system is easier to control because Jacobian matrix of joint-angle and muscle-lengths does not depend on the angle of the joint, ball-socket has more simple structure and less number of parts. Kenta's structure is the latter because of Kenta's huge degrees of freedom. Each ball-and-socket joint (spherical joint) is driven by four tendons. By arranging each tendon slantingly, the movable range of yaw-angle is expanded.

Legs: The left figure of Fig. 7 shows the arrangement of DOF of Kenta's legs. Each crotch joint has 3 DOF, each knee joint has 1 DOF, and each ankle joint has 3 DOF. The movable range of hip and ankle joints is 55 degrees in roll and pitch rotation, and 45 degrees in yaw angle. The right figure of Fig. 7 shows 3D view

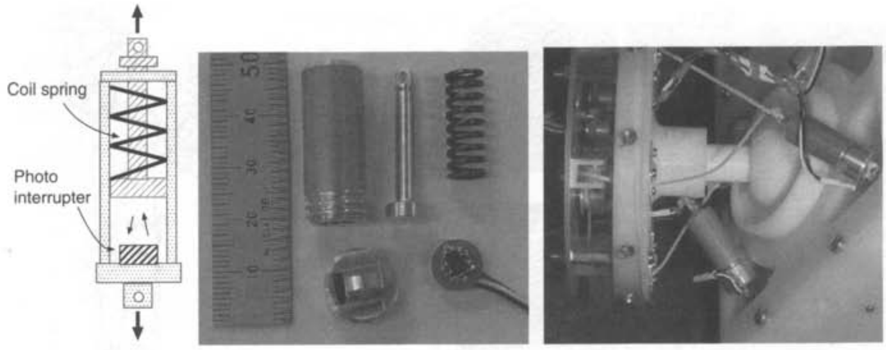


Fig. 9. Left: tension sensor unit with a photo interrupter, Right: crotch joint

of Kenta's leg in 3D CAD software. Motors to pull the muscles are embedded in the thigh and calf. Each leg is equipped with 10 motors.

Arms: The left figure of Fig. 8 shows the arrangement of DOF of Kenta's arm. Each shoulder consists of two ball-socket joints as shown in the left of Fig. 8. It is closer to human's shoulder's movability than conventional single-jointed shoulder. The right figure of Fig. 8 shows 3D view of Kenta's leg in 3D CAD software. Motors to pull the muscles are embedded in the structure. Each arm has 14 motors.

2.6 The sensors of Kenta

Muscle-length sensors: By measuring the lengths of muscles, it is possible to control the lengths. All of Kenta's muscles are actuated by geared DC-motors, each of which is equipped with a rotary encoder. The lengths of muscles are calculated using the signal of the rotary encoders. One thing to be noticed is that the relation between the numerical value of rotary encoder and the angle of motor's axis is not linear since using pulley.

Muscle-tension sensors: By measuring the tensions of muscles, it is possible to control the tensions. The antagonistic muscles to drive a joint always have to have tensions. Every muscle of Kenta has a tension-sensor. Figure 9 shows the tension-sensor unit attached to Kenta's muscles. When the tension of the wire changes, the length of the coil spring in the cylinder. 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 light emitting diode and infrared photo transister.

Motor-current sensors: In the motor-driver circuit, there is a $0.5[\Omega]$ resister connected in series in the motor-power line. By measuring the drop of the voltage through the resister, the motor-current can be detected.

Vision sensors: Kenta is equipped with two CCD color cameras. Using the two cameras, it can calculate the depth by stereoscop. The depth map, 3D optical flow, color labeling, plane segment finder (Okada, Kagami, Inaba, Inoue, 2001), etc. are implemented.

3D-accelerometers and gyroscope: There are eight 3-axis-accelerometers; in the hip, five vertebrae, the chest, and the head. They help to detect the information about the posture of the spine, and the information on Kenta's inclination, by detecting the vector of gravity force. There is also a gyroscope in the head block. Reflective eye motions are done using this sensor.

Tactile sensor: Kenta has 62 tactile sensor unit (FSR: force sensing register). By using them, Kenta can obtain information of contact to the environments. These sensors can be also used for direct teaching of posture. By touching the tactile sensors directly, human can teach postures and motions.

3 Design of the Software System Structure

In order to handle the 96 actuators and over 400 sensors, Kenta's control system is based on distributed system, that provides extensibility of sensor and actuator units. The left figure of the Fig. 10 shows the software system diagram of Kenta.

Layers: It consists of three layers. The bottom layer is the system in Kenta's body, and top two layers are in the remote host computer. The lowest layer is the onbody-LAN, which connects about 45 distributed microprocessors. Each microprocessors has the interface for a multi-master serial-bus called I^2C-bus, 8 AD converters, 16 PWM generators. The middle layer was named nervous system and works as a hardware abstraction layer. The data flow between the middle layer and lower layer(onbody-LAN) is hardware-dependent; AD value of tension-sensors or counted pulse of motor-encoders. The interface between upper layer is body-independent; numerical values are in physical quantity. The top layer contains a geometric model of robot, motion data, and other high level softwares.

Communication System: The right figure of the Fig. 10 shows the onbody-LAN of Kenta. There are four subnets; hip-network, chest-and-head-network, arms-network, and legs-network. In each subnet there is a hub processor. Each hub processor collects sensor information from distributed processors connected to the subnet and sends them to the HostPC through high-speed serial line, and receive actuator-control information from the HostPC and distributes them to the dispersed processors through the onbody-LAN. We have developed some kinds of electric circuit boards to construct the onbody-LAN and distributed controllers (Fig. 10).

Hardware abstraction layer: The hardware abstraction layer called 'nervous system', the middle layer in the left figure of the Fig. 10, communicates with the hubs of the onbody networks. It is also a TCP/IP socket server (interface for the upper layer). When a request for connection from an upper layer (Software or character-UI), it opens a connection and starts to send/receive sensor/actuator information to/from the upper layer.

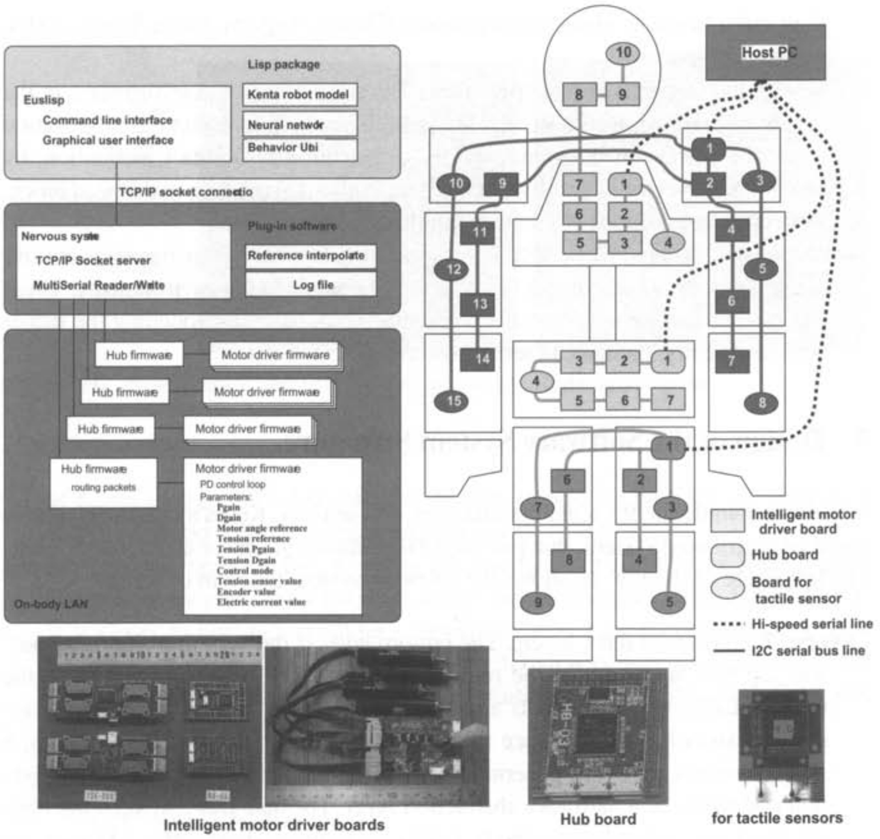


Fig. 10. Software system of Kenta (left: block diagram, right: the onbody-LAN, bottom: developed circuit boards)

Top level software: The geometric model of Kenta is implemented at the top layer of the three layers. By using the model, the calculation of muscle-length from posture of joints, the inverse calculation (posture of joints from muscle-length) using a neural network, etc. can be done. The geometric model of the robot is written on an object-oriented lisp, EusLisp (Matsui, Inaba, 1990). In the model, there are classes of ball-and-socket joint, rotational joint (knees and elbows), links, and wires (muscles). When rotating Kenta's joints in the model, the changed posture of Kenta is shown in the graphical window.

4 First steps to manage the body

4.1 Geometric model and muscle control modes

One method to manage the body is using a geometric model in conjunction with some control modes of muscles (Mizuuchi et al., 2001). The geometric model can

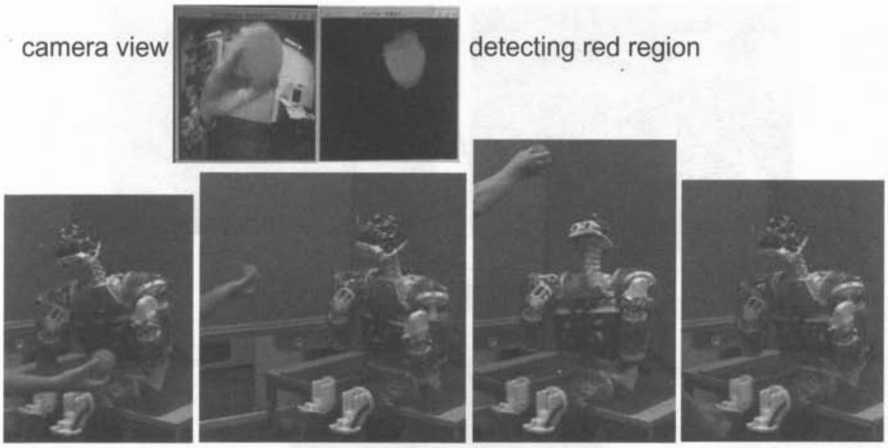


Fig. 11. Tracking an object by coordination of eye-balls, neck, and spine

approximate the lengths of muscles of any posture of the body. Depending on the posture, the error range of the muscles' lengths could be a certain extent. When there are some interferences between the muscles and bodies, if the muscles are controlled in the length-control mode, motors have to generate large torques. To avoid such case, muscles can be controlled in other control-mode using the tension-sensors' information. By using the information of tension sensors, muscle's tension can be limited. These control modes are implemented in the onbody microprocessors and the cycle of the control is 1 millisecond. In Fig. 11, Kenta is tracking a color object by coordination of eye-balls, neck, and spine. Vision processing of object-tracking is done in a remote host computer. Each of the eye-balls, neck and spine is independently tracking the object, and the three gains of the tracking-control are adjusted to balance the task.

4.2 Direct teaching

A simple and strong way to make whole-body motions of a complex structure is direct teaching. By controlling all muscles in the tension-control mode, each tension of them is kept in a constant value. When we directly change the posture of the robot in this condition, the lengths of all the muscles are modified to keep the tension. By recording the lengths while directly teaching, we can obtain the possible combinations of the lengths. At the stage of playing back, the muscles are controlled in the length-control mode, so as to reproduce the posture or the motion.

Figure 12 shows a motion using some directly taught postures. In (T1) and (T2) of the figure, two postures are being taught by a man touching directly. (P1), (P2) and (P3) of the figure shows three postures recorded at the teaching phase. (P2) and (P3) correspond with (T1) and (T2) respectively. By the combination of the postures directly taught, some motions are realized.

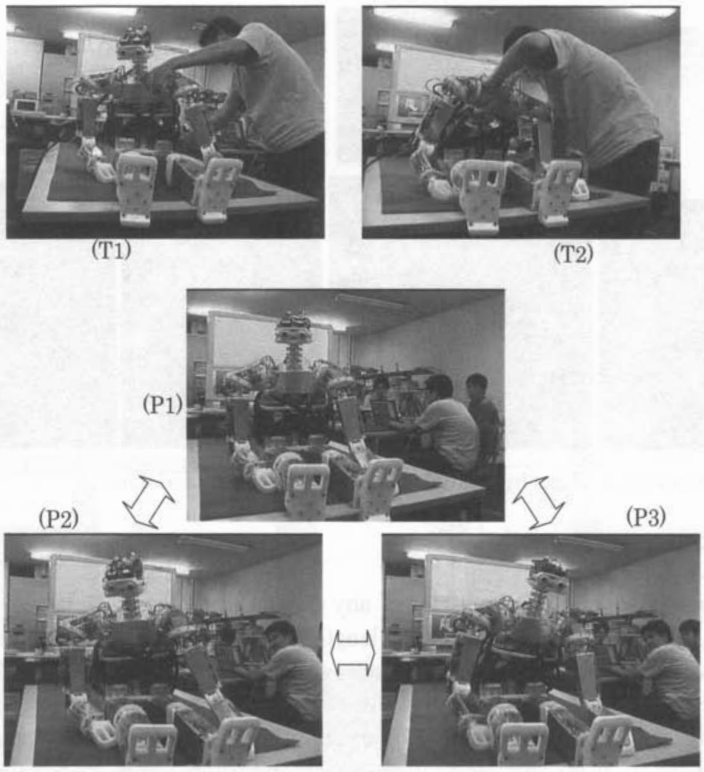
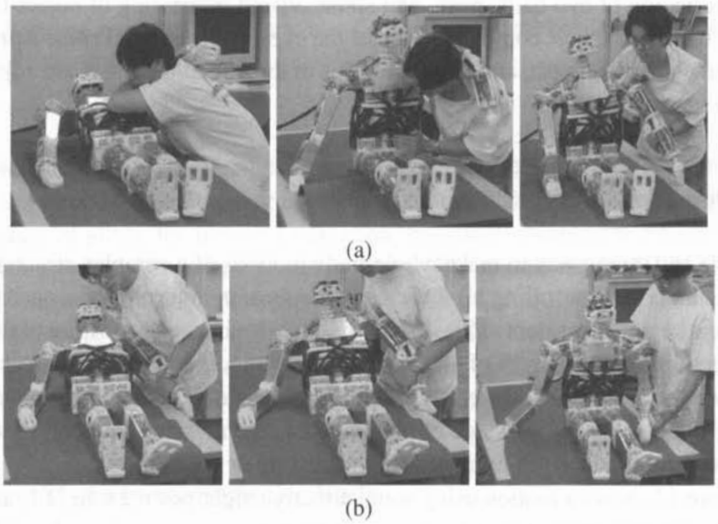


Fig. 12. Teaching postures and playing back them


(a)

(b)

Fig. 13. Experiments of teaching movable space (a)passive mode (b) replay with partially passive mode

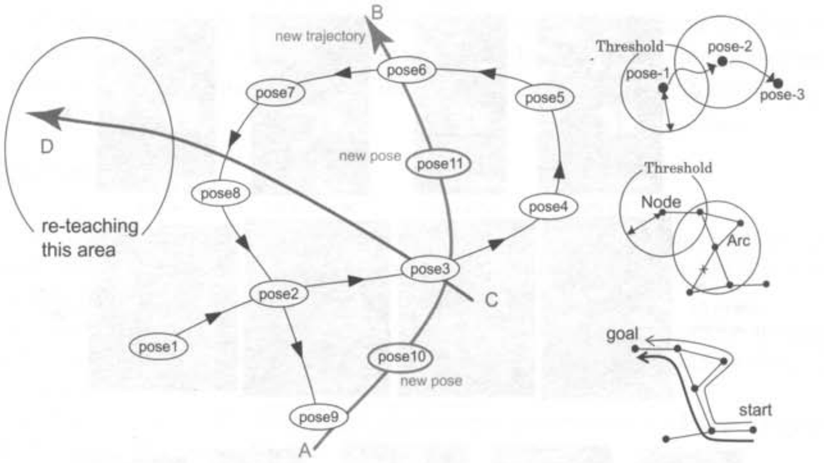


Fig. 14. Left: the concept of posture database, Right: (top: creating new nodes automatically using a threshold, middle: creating and trimming arcs, bottom: path-planning)

Figure 13 shows an experiment to teach getting up motion. The sequence (a) is the motion in fully passive mode. In the sequence (b), the robot follows the selected joints of the sequence (a).

4.3 Automatic expansion of motion space

It is quite difficult to decide the lengths of all muscles so as to take a posture, because the structure of Kenta's spine and whole-body is very complex. Even the geometric model described in Section 4.1 cannot derive the precise lengths of muscles. To help the directly teaching, we use the 'posture database'. The left figure of the Fig. 14 shows the concept of it. This database is automatically created when the robot moves. The element in the database includes the information of the muscles' lengths and 3D-accelerometers. The elements are segmented by the sensor information. When the distance between a data and each element of the database is larger than a threshold, a new node created by the data will be added to the database(see the top figure of the right side of the Fig. 14). In the left figure of the Fig. 14, pose1 to pose9 are automatically generated in some motion. Pose10 and pose11 are created in the other motion of A to B. The elements of the database are guaranteed to be a combination of the muscle-lengths without the interference. The amount of data which should be recorded can be lessen compared to recording the postures at all instances.

Figure 15 shows a whole-body motion including spine-motion, which is generated by direct-teaching and using the posture-database and posture-history.

We can use the postures of the database to develop motions and also obtain a new motions using the postures of the database. There are the arcs connecting nodes (elements of the database). The arcs are firstly defined as paths which robot

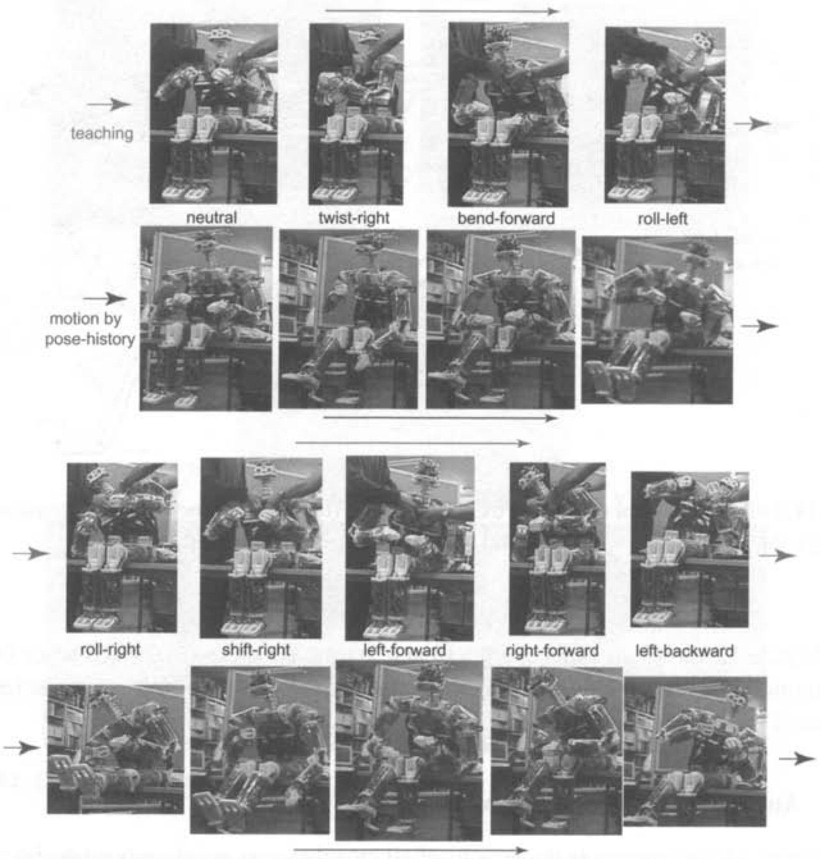


Fig. 15. A motion using pose history

once followed. There also can be new arcs which robot has not followed because there are some couple of nodes near enough to create a new arc (see the middle figure of the right side of the Fig. 14).

5 Summary and Concluding Remarks

This paper describes the design concept and its implementation of a spined muscle-tendon humanoid "Kenta". First steps of controlling Kenta's body including the ten-jointed spine are also described; calculation of muscle-length and joint-angle using a geometric model, realization of tracking motion, direct teaching and playback, and a method of automatic expansion of motion space.

In the future, humanoids will be expected more sorts of tasks and their bodies will be more complex. At that stage, the software which can manage the complex body and many various redundant incomplete information will be cruicial. Human can manage his complex body using such huge information. Kenta can be one of

the testbeds for studying such kind of brain software. This research has been supported by Research for the Future Program of the Japan Society for the Promotion of Science: Micro-Mechatronics and Soft-Mechanics (JSPS-RFTF96P00801).

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