Development of Power Assisting Suit for Assisting Nurse Labor*

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In order to realize a power assisting suit for assisting a nurse caring a patient in her arm, a hardness sensor of muscle using load cell and a pneumatic rotary actuator utilizing pressure cuffs have been developed. The power assisting suit consists of shoulders, arms, waist and legs made of aluminum, and is fitted on the nurse body. The power assisting suit is originated with the concept of a master and slave system in one body. The arms, waist and legs have the pneumatic rotary actuators. The pneumatic rotary actuators are constructed with pressure cuffs sandwiched between thin plates. The action of the arms, waist and legs of the nurse are sensed with the muscle hardness sensor utilizing load cell with diaphragm mounted on a sensing tip. The dent of the sensing tip corresponds to the hardness of the muscle so that exerting muscle force produces electric signal. This paper gives the design and characteristics of the power assisting suit using the cuff type pneumatic rotary actuators and the muscle hardness sensor verifying its practicability.

Key Words: Human Interface, Control Device, Measurement, Power Assisting suit, Pneumatic Rotary Actuator, Pressure Cuff, Master and Slave System in One Body, Muscle Hardness Sensor, Road Cell

1. Introduction

In recent years in Japan, the percentage of the aged (65 years and over) has been increasing in unexpected speed, much faster than any other countries have faced. In the year 2010, everyone out of five persons will be 65 years and over, twice the present number. Recently, the development of the welfare machine which met old man's needs is an important subject caused by the rapid aging. The research of the robot which aimed at supporting transfer movement of a patient was begun in the generation in 1970, and MEL-Kong[(1)] was that representative example, and an operation robot Nurcy[(2)] by master and slave control system was developed. But, all of this doesn't stand on the prospects for the utility yet.

Recently, the development research to solve this problem becomes active. The device[(3)] which supports patient's transfer movement and the device[(6)] which supports the movement of taking up a patient in one's arms were proposed. These aim at reducing the burden of the waist of the care person. These devices used electric motors as actuators. For assisting walking motion, an exoskeleton power assist hybrid assistive leg[(4)] using an motor and bowl-screw actuator, and an active outfit[(5)] for knee motion using pneumatic actuators were developed.

The development of helping equipment for practical use is urgent necessity. To help those who have difficulties in daily basic movements, such as rising, laying, walking, etc., mechanical device which might give unpleasant or uneasy insecure feeling to them are not acceptable. However, to leave the matter only to man-power cause great physical burden to the attendant nurse. Hence, a device which lightens hard physical labor and still gives tender touch is the ultimate goal in our study. We think that a care person must secure safety.

We began with powered arms, waist and legs that combined each other constructing a suit to be applied to a nurse. The problem here was to design the mechanisms of the arms, waist and legs actuator which give power smoothly following the movement

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of a human body. We developed the powered arms and legs using rubber tube actuator[(7)-(11)]. It was small but powerful actuator using air pressure to expand or contract the tube. But it had remarkable hysteresis in its performance characteristics. Then, we developed a pneumatic rotary actuator[(12)-(15)] which consists of concentric round boxes sliding each other. The powered suit using this rotary actuator had a possibility of good quality in smoothness and tenderness, but it had weak points of solid friction and over weight. In order to overcome the week points, we improved the pneumatic rotary actuator utilizing pressure cuffs[(19)-(22),(24),(26)].

For realization of power assisting suit assisting smoothly the movement of the arms, waist and legs of a nurse during the sequential operation of holding up and down of a patient, the sensing systems of the necessary assistant forces for the joints of arms, waist and legs are necessary. In the beginning, for detecting the movement of the arms, waist and legs, the sensors inserting a conductive rubber or a pressure cuff into the gap between the unit and the muscle were developed[(7)-(11)]. But, these were insufficient for the realization. We thought that it is good to give each joint the assistant power corresponding to the power which the muscle driving each joint shows. So, we proposed the method to detect the generated muscular force by the hardness of muscle. Novel muscle hardness sensors were developed for sensing of the hardness of muscles. The sensor consisting of a contact projection on a rubber diaphragm which detects the hardness of the muscles of the arms, waist and legs were developed[(11)-(13)]. But, this muscle sensor was sensitive against the temperature of muscle. In order to overcome the week points, we developed the muscle hardness sensor with a contact projection on a sensing diaphragm of a load cell[(16)-(26)].

This paper gives the design and the characteristics of a new power assisting suit utilizing improved muscle hardness sensor and rotary actuators. The characteristics of the power assisting suit proved the possibility that the suit stood up to utility.

2. Power Assisting Suit

The basic design concepts of the power assist suit have four points, that is,

1. An absolutely safety system, that is, the system must be ready for all emergencies. This is assured by the controllability by the nurse, that is, the assisting system is a master and slave system in one body.
2. With no mechanical part in front of the suit so that the arms and breath of the nurse could be contact directly to the body of the patient carried in her arms. This structure gives good feelings between a patient and a nurse.
3. With flexible joints. This is realized by developing a pneumatic rotary actuator using pressure cuff like a balloon. The joints with this pneumatic actuator give tender touch to the arms, waist and legs of the nurse.
4. Assisting forces corresponding to the necessary forces to bend and stretch the joints. This is realized by detecting the force exerted in the muscle driving joint. By this sensing system, smooth movements of the arms, waist and legs of the assist suit are made possible.

Construction of the newly designed power assisting suit is shown in Fig. 1. The power assisting suit was composed of power assisting arms, waist and legs. The joints of the elbows, waist and knees were rotated by newly developed pneumatic rotary actuators. Materials of these units are aluminum. When she stands upright, whole weight of the suit can be supported by the leg units. While she bends the waist or knee, the weight can be supported by the actuators. Total weight of these units is 13.4 kg.

Sensing and control system of the power assisting suit is shown in Fig. 2. Muscle forces of the arms, waist and legs of a nurse were detected by the muscle hardness sensor using a load cell. The muscle sensors were applied to her upper arms, legs over the knees and back over the hip, respectively. When the nurse raises her arms, straightens her back and stretches her knees, the hardness of the muscles of her arms, back and legs increase and the output signals of the sensors increase. Increases in the output signals are transformed into the increases in the supply voltages of the solenoid valves through the computer and the PWM driving circuits, so that the supply air flows to

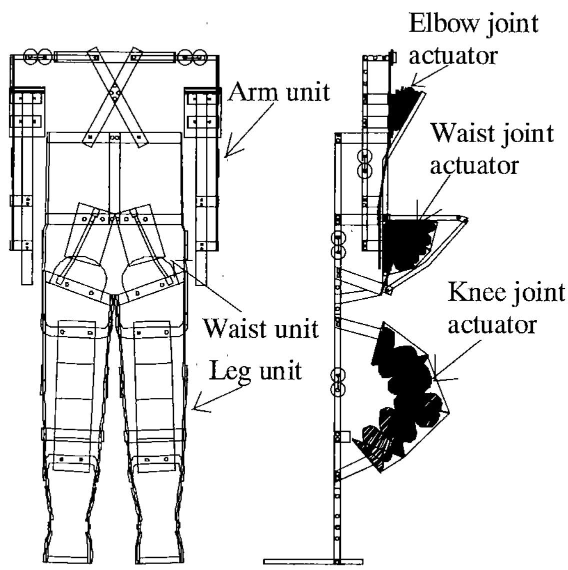


Fig. 1 Power assisting suit

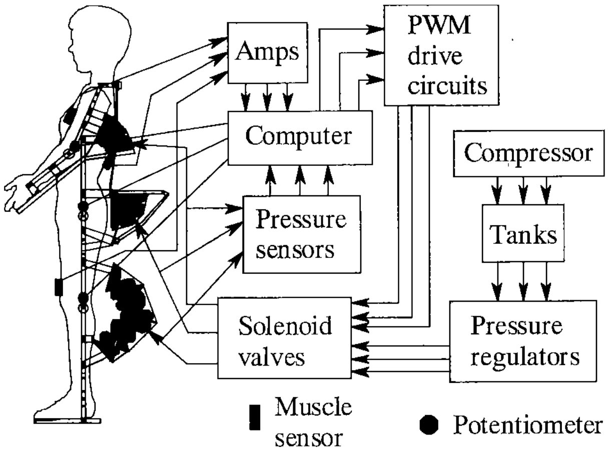


Fig. 2 Sensing and control system of power assisting suit

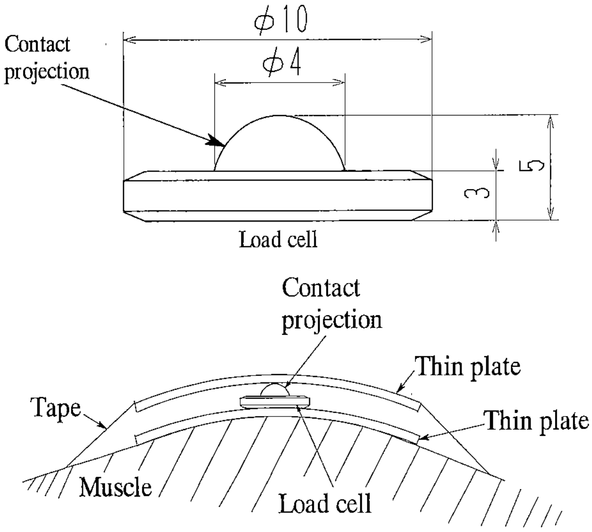


Fig. 3 Construction of muscle hardness sensor

the cuffs increase. Then the rotary actuators produce the torque which drives the elbow joints, the knee joints and the link work assisting the straightening of her back.

3. Muscle Hardness Sensor

A novel muscle sensor was developed for sensing of hardness of muscle which corresponds to the force generated in the muscle.

3.1 Construction of muscle sensor

As shown in Fig. 3, the muscle sensor consists of a contact projection on a sensing diaphragm of a load cell. By sandwiching the sensor with thin plates and applying to the muscle, the hardness of the muscle is detected as the output signal which corresponds to the depression of the projection.

3.2 Suitable detecting points of muscles

It was necessary to find out the most suitable detecting points of the muscles driving elbow, waist and knee joints. Figures 4 - 6 show the optimum

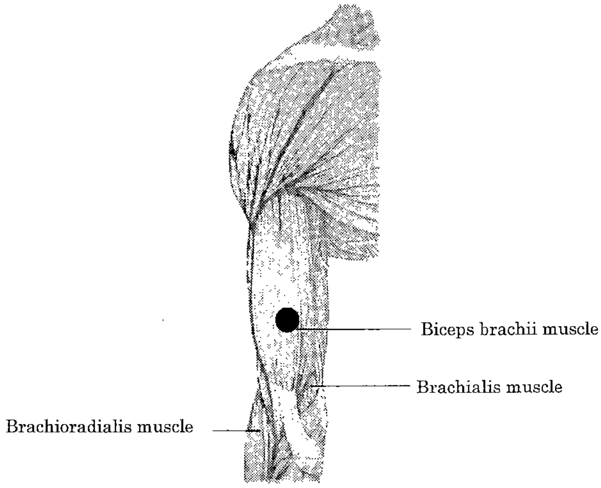


Fig. 4 Optimum points for detecting hardness of muscle driving elbow joint

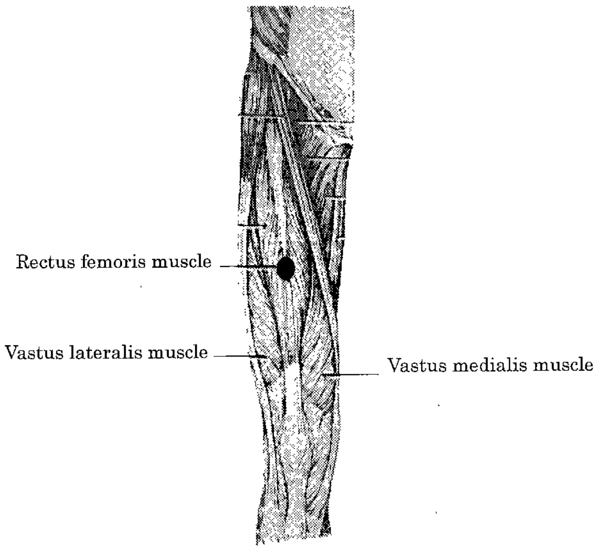


Fig. 5 Optimum points for detecting hardness of muscle driving knee joint

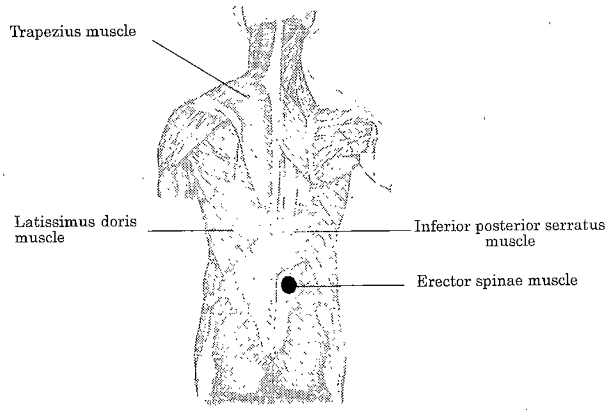
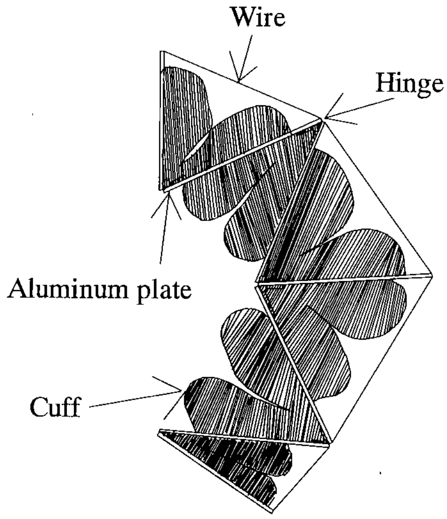
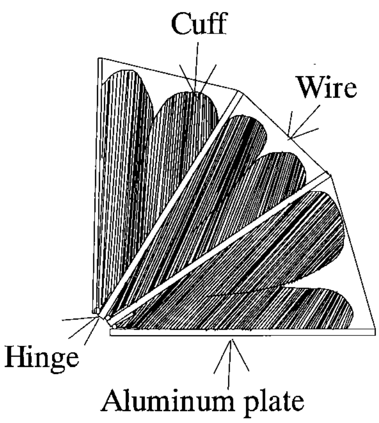


Fig. 6 Optimum points for detecting hardness of muscle driving waist joint



(a)



(b)

Fig. 7 Pneumatic rotary actuators, (a) pneumatic rotary actuator of elbow and knee joints, (b) pneumatic rotary actuator of waist joint

points for detecting the hardness of the muscles driving each joints. The point for elbow joint was on the biceps brachii muscle, that for waist joint was on the erector spinae muscle, and that for knee joint was on the rectus femoris muscle.

4. Pneumatic Rotary Actuator

The new models of the pneumatic rotary actuators of elbow, knee and waist joints are shown in Fig. 7. These rotary actuators are constructed with pressure cuffs of a sphygmomanometer sandwiched between thin plates. The thin plates are connected at one end in the case of the actuator for waist joint, so that the plates spreads as a fan by supplying air pressure in these pressure cuffs, producing torque, then the actuator provides rotational motion. On the other hand, they are connected each other at both ends and zigzagged in the case of that for elbow and knee joints. The plates extend in an arc by supplying air pressure in these pressure cuffs, producing torque, then the actuators provide rotational motion. Weights of the rotary actuators for elbow and knee joints are 1.5 kg, and that for waist is 0.85 kg.

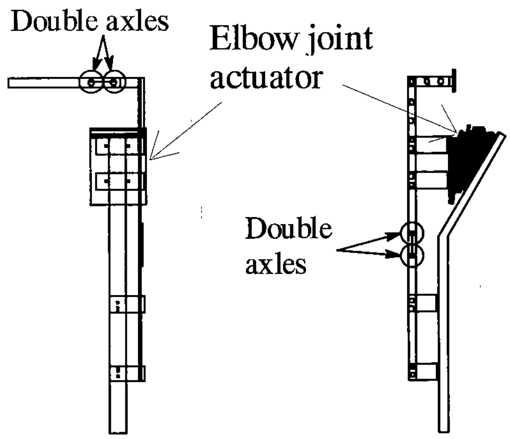


Fig. 8 Power assisting arm unit

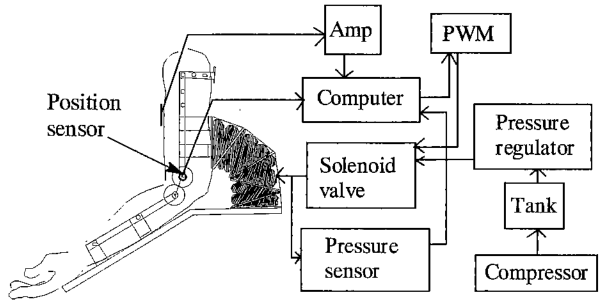


Fig. 9 Sensing and control system of arm unit

5. Power Assisting Arm Unit

Power assisting arm unit must be attached to the nurse's arm and supports the action of the arm in accordance with the movement of her arm. Construction of the power assisting arm unit is shown in Fig. 8. Shoulder has two joints, one can swing back and forth and the other can swing side to side. Similar to an artificial limb, elbow unit has double axles so that the unit can bend following the bending of the arm. The material of the arm unit is aluminum. Rotatable range of the elbow joint is 60 degrees. The weight of the arm unit is 2.1 kg.

Sensing and control system of power assisting arm is shown in Fig. 9. Muscle sensor is applied to her upper arm. When the nurse raises her arms, the hardness of the muscles of her upper arms increases and the output signals of the sensors increase. Increases in the output signals are transformed into the increases in the supply voltages of the solenoid valves through the computer and the PWM driving circuits, so that the supply air flows to the cuffs increase. Then the rotary actuators produce the

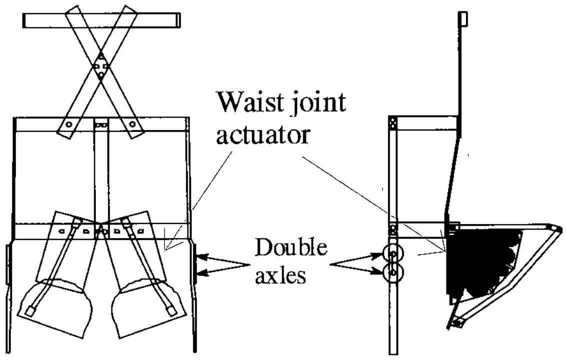


Fig. 10 Power assisting waist unit

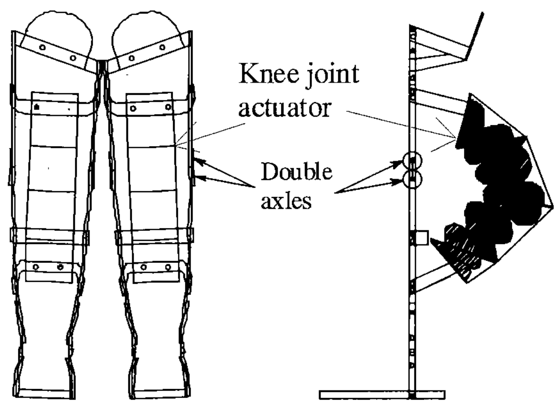


Fig. 12 Power assisting leg unit

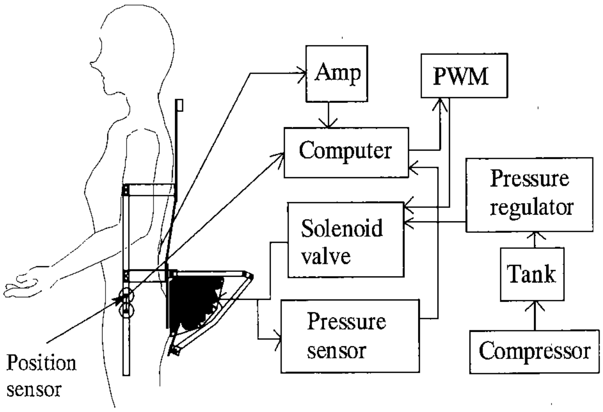


Fig. 11 Sensing and control system of waist unit

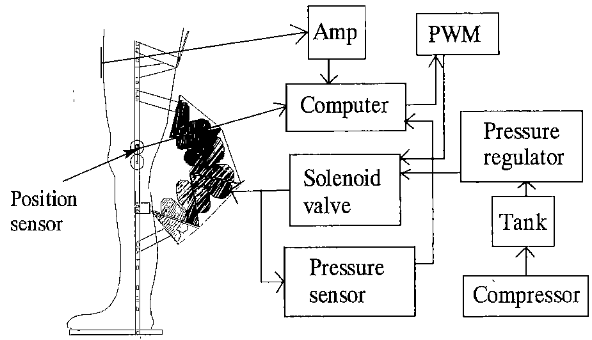


Fig. 13 Sensing and control system of leg unit

torque driving her elbow joints and assist the raising of her arms. Only proportional control is used to control the cuff pressure.

6. Power Assisting Waist Unit

The construction of the power assisting waist unit is shown in Fig. 10. The waist unit is carried on the nurse's shoulder. The force produced by the rotary actuator is transmitted to the body of the construction by a link work. Rotatable range of the waist joint is 90 degrees.

Power assisting waist system is shown in Fig. 11. Muscle sensor is applied to her back over hip. When the nurse straightens her back, the hardness of the muscle of her back increases and the output signal of the sensor increases. Increase in the output signal is transformed into the increase in the supply voltage of the solenoid valve through the computer and the PWM driving circuit, so that the supply air flow to the cuffs increase. Then the rotary actuator produces the torque driving the link work and assists the straightening of her back. Only proportional control is used to control the cuff pressure.

7. Power Assisting Leg Unit

The construction of the power assisting leg unit is shown in Fig. 12. Similar to the power assisting arm unit, the pneumatic rotary actuator drive directly the knee joint of the unit. Rotatable range of the leg joint is 70 degrees.

Power assisting leg system is shown in Fig. 13. Muscle sensors are applied to her legs over knees. When the nurse stretches her knees, the hardness of the muscles of her legs increases, so that the output signals of sensors increases. The increased output signals are amplified and converted into the increases in the supply voltages of the solenoid valves through the computer and the PWM driving circuits, so that the output air flows of the valves increase. Increased output air flows produce the torque assisting the stretching of her knees. Only proportional control is used to control the cuff pressure.

8. Experimental Results

8.1 Muscle hardness sensors

The characteristics of the muscle hardness sensors applied to the muscles of arm, waist and leg during the sequential movements of bending and stretching the arms, waist and legs are shown in Fig. 14. The loads were applied by barbells held in both hands. The output signals of the muscle sensors were amplified by DC amplifiers. The angle $\theta=0$ corresponds to fully stretching the arms, waist and legs.

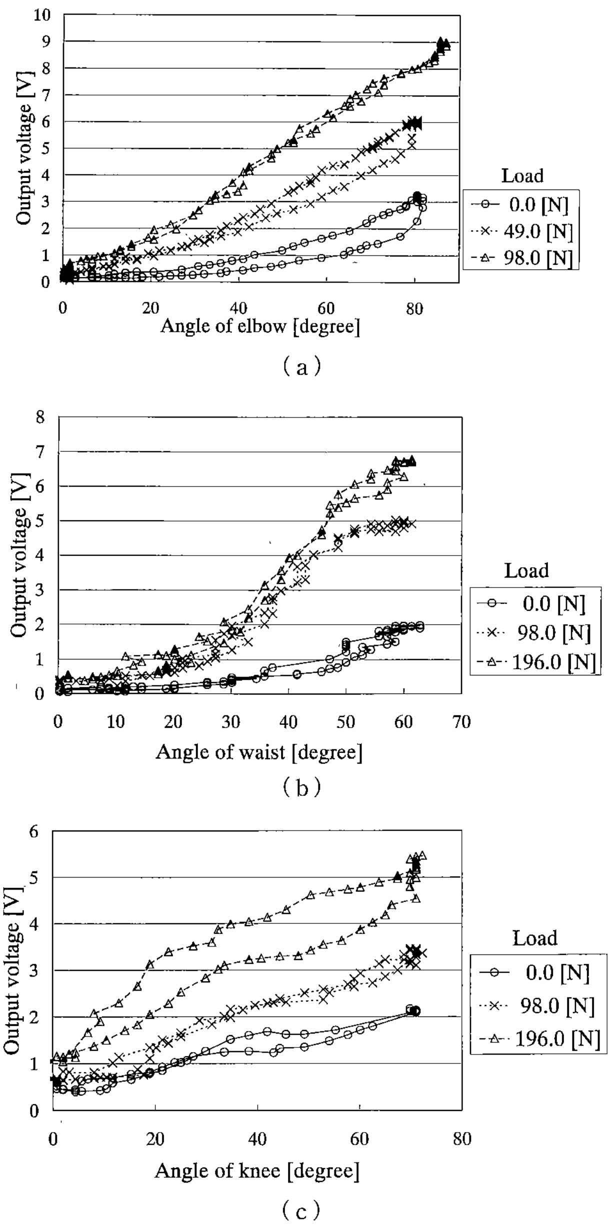


Fig. 14 Conversion characteristics of muscle hardness sensors, (a) arm muscle hardness sensor, (b) waist muscle hardness sensor, (c) leg muscle hardness sensor

The output signals of the muscle sensor applied on the biceps brachii muscle of her arm were almost proportional to the bending angle of the elbow joint. They had enough sensitivity for the weight load though hysteresis existed in light weight load. On the other hand, the output signals of the sensor applied on the erector spinae muscle of her waist muscle showed rather parabolic than linear relation to the bending angle of the waist joint with the least hysteresis. The output signals of the sensor applied on the rectus femoris muscle of her leg muscle showed almost linear relation to the bending angle of the knee joint with hysteresis in heavy weight load.

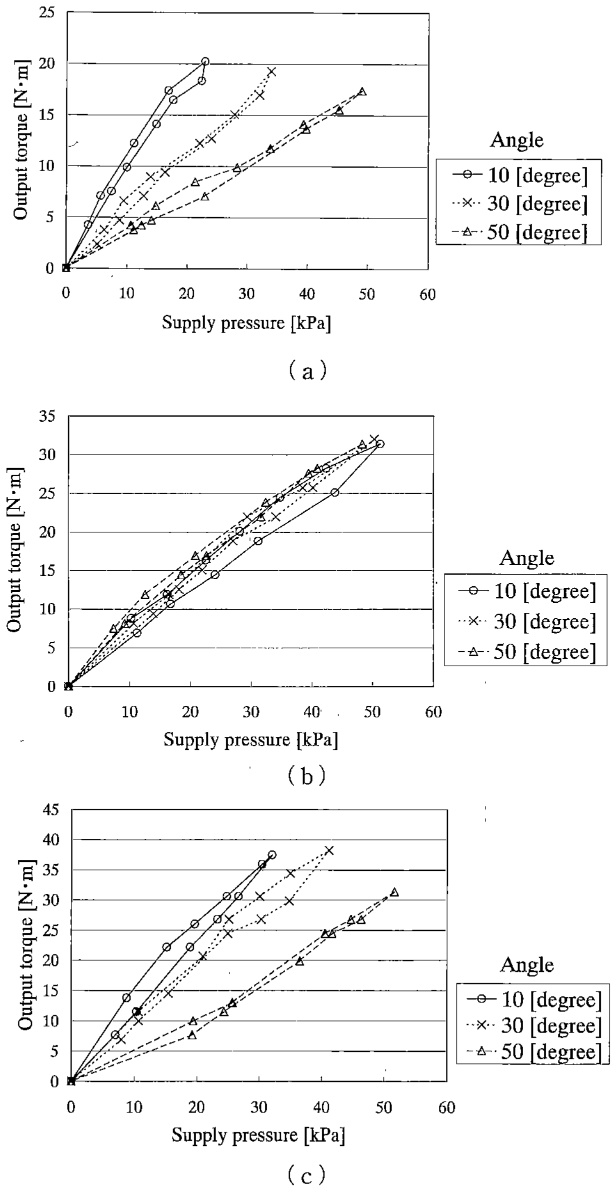


Fig. 15 Characteristics of actuators, (a) elbow joint actuator, (b) waist joint actuator, (c) knee joint actuator

These characteristics showed the applicability of this muscle sensor.

8.2 Rotary actuator

Figure 15 shows the output torque versus supply pressure characteristics of elbow, waist and knee actuators on the condition that these actuators were attached to their respective units. The output torque was measured by using a spring scale keeping at a right angle to each unit's member functioning as a moment arm. The relations had the linearity with slight hysteresis.

The rotary actuators for elbow joint and knee joint were almost same in configuration and size, therefore, they had almost same characteristics. The conversion ratios depended on the angles of joints.

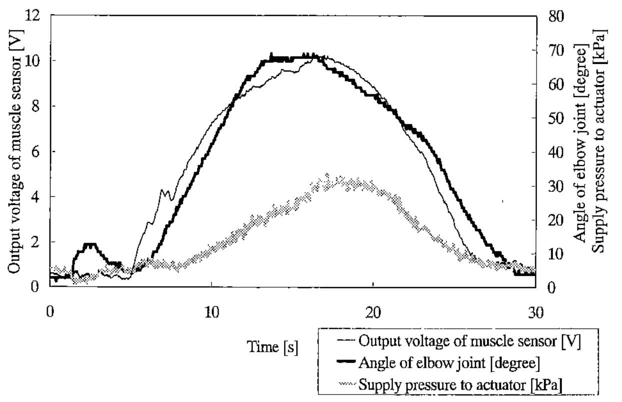


Fig. 16 Operation characteristics of arm unit

This was due to the construction of the actuators, i.e., in the case of the actuators for elbow and knee, thin plates were connected each other at both ends and zigzagged, so that the plates extended in an arc. But on the other hand, in the case of the actuator for waist, thin plates were connected at one end, so that the plates spread as a fan.

8.3 Operation characteristics

Operation characteristics were measured by applying practically the power assisting suit to a human body and operating holding up and down the weight of 20 kgf in the hand, i.e., the simulated operation of holding up and down of a patient.

8.3.1 Power assisting arm unit Operation characteristics of the arm unit are shown in Fig. 16. In this figure, the relationship between the supply pressure to the actuator, the output voltage of the muscle sensor and the rotational angle of the elbow joint of arm unit are shown. Zero degree corresponds to fully stretching of the elbow. As shown in this figure, the hardness of the arm muscle could be detected by the sensor, so that the supply pressure of the actuator changed according to the necessary torque, and the elbow joint of the arm unit could rotate smoothly following the up-down of the human arm. Referring to the characteristics of the elbow actuator (Fig. 15(a)), it is estimated that the arm unit produced the maximum torque of about 10 Nm. This value is about a half of the necessary torque 22 Nm estimated by body mechanics.

8.3.2 Power assisting waist unit Operation characteristics of the waist unit are shown in Fig. 17. Zero degree corresponds to fully stretching of the waist. The hardness of the back muscle driving the waist could be detected by the muscle sensor, then according to the necessary torque, the supply pressure changed, and the joint of the waist unit rotated smoothly following the motion of the human waist. Referring to the characteristics of the waist actuator (Fig. 15(b)), it is estimated that the waist unit produced the maximum torque of about 30 Nm. This value is about a half of the necessary torque 65 Nm estimated by body mechanics.

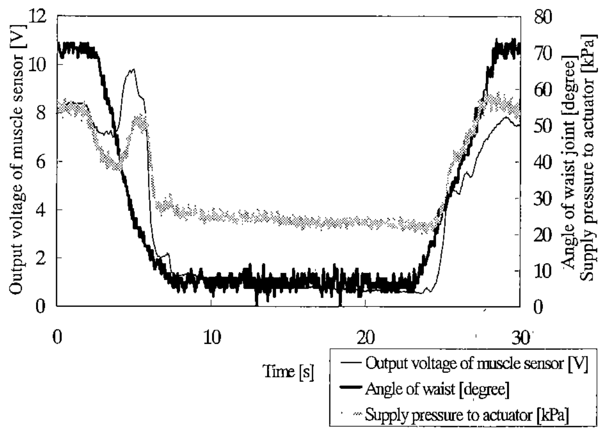


Fig. 17 Operation characteristics of waist unit

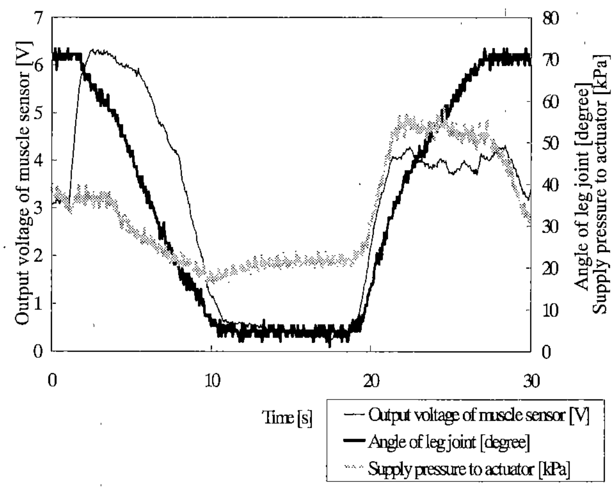


Fig. 18 Operation characteristics of leg unit

8.3.3 Power assisting leg unit Operation characteristics of the leg unit are shown in Fig. 18. Zero degree corresponds to fully stretching of the knee. The hardness of the leg muscle could be detected by the muscle sensor applied to the front of the leg. Although the supply pressure could not follow the output voltage of the muscle sensor at stretching of leg, the joint of the leg unit could rotate smoothly following the bend and stretch of the human leg. Lack in the supply pressure at the knee stretching was brought about because the air supply system could not make up the shortage of air supply due to the increase in the volume of the pressure cuff at the stretching. Referring to the characteristics of the knee actuator (Fig. 15(c)), it is estimated that the leg unit produced the torque of about 15 Nm at the beginning of the stretching, i.e. at most active phase. This value is about a half of the necessary torque 30 Nm estimated by body mechanics.

9. Concluding Remarks

A new power assisting suit applying to a human body was developed. The suit was composed of power assisting arms, waist and legs units having joints with double axles. The suit was originated with the concept of a master and slave system in one body.

A new muscle hardness sensor using load cell was developed. The muscle sensor could detect the exerting forces of the muscles driving elbow, waist and knee joints.

A new pneumatic rotary actuators utilizing pressure cuffs were developed. The pneumatic rotary actuators have many advantages, i.e., simple structure, light weight, and has possibility to realize supple movement with linear characteristics without hysteresis.

The power assisting suit was applied practically to a human body and held up and down weights in the arms. Each unit could transmit assisting torque directly to each joint verifying its practicability. If the movement of the care was done slowly with ascertaining the generating of the assistant torque, the units could follow the movement and the wearer could feel the movement of the care to be helped by the suit.

At present, we proceed with the improvement toward the utility about the following subject,

① The suit which compose of the component parts that have enough strength for the light weight design,

② The actuator which has the form satisfying a gap exactly for the improvement in linearity,

③ The stable application method of muscle sensor to waist muscle,

④ The air supply system which makes up for the shortage of air supply to the leg unit,

⑤ The control method which use not only sensing values but also theoretical values based on body mechanics.

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