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Paper:

An Analysis of Human Motion for Control of a Wearable Power Assist System

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The purpose of this study is to build a control system for a wearable power assisting device, which helps people with lifting heavy things, like a person who can't move alone in daily life. When we lift something heavy, we use both hands. That's why a control system that can automatically switch on/off without using hands is necessary. In this study, we analyze human lifting up motion, and reveal characteristics of the motion, to find the suitable timing for switching the wearable power assisting device. Results show that the automatic switching can be realized.

Keywords: power assisting device, wearable robotics, electromiogram (EMG)

1. Introduction

Our recent aged and aging society increases the number of people who work for daycare, which is getting heavier and more frequent, particular for the support of moving an aged or disabled person who cannot move around by himself. Not only the supported person, but also the supporting person can be injured himself by the heavy load of the support, particularly in a lower back. According to a report [1], most of nurses have had lumbago. However they had few measures against lumbago. Therefore, we need a mechanical supporting device for the assisting person for protecting his lower back.

In this paper, we analyze human lifting motion, and reveal characteristics of the motion, to control the power assisting device. It is necessary that this device becomes smaller and lighter to reduce loads. Add to this, people use both hands when they lift something. So a control system which can automatically switch on/off without using hands is necessary, too. On this basis, we analyze human lifting and putting down motions in order to find suitable timing for switching this device.

2. Related Works of Design of Wearable Power Assist Device

There are several projects about a wearable power assist device. Target portions of assisting are arms, legs, back, and so on. In this section, power assist devices including a lower back are summarized.

First of all, there is the project of Exoskeletons for Human Performance Augmentation (EHPA), which John A. Main et. al. are carrying out at Defense Science Office (DSO), Defense Advanced Research Project Agency (DARPA), USA [2]. The purpose of this project is to be used by soldiers, that have to move long-distance with heavy loads. Because of the purpose, they are interested in walking or running with heavy loads. So, they analyze a gait of walking in these conditions.

The full body type assist system is developing also in Kanagawa Institute of Technology, which is called "Wearable power assist suit" [3,4]. The device is designed for daycare, so their target load is about 60kgf and the device supports many DOFs of a full body. They use air cylinders as the actuators which requires a big compressor for energy supply. Therefore, the total weight of the device becomes heavy. The sensors for detecting human motion are based on the hardness of a skin surface. When we generate a large force, associated muscles become hard. They use it to estimate forces. So the sensors are more resistant to noise.

Another one is "HARO" (Human Assist RObot) made by the University of Electro-communications, Japan [5,6]. The device is designed for daycare, too. This device supports left and right arms. Looking from outside of the device, a supported person looks wrapped by the device, so the load of a person is not so large. However, because of the large size of the device, it needs a large room to set up. The whole device is supported by a stable body and actuated by DC motors. The sensors for detecting the power are measuring a current of each of the motors, that reflects an output torque of the motor and an applied load to the motor.

Contrastively, Tsukuba University, Japan, made a light downsized power assist device named "HAL" (Hybrid Assist Leg) [7,8]. Its actuators are DC motors in order to give a timing for walking. But the force that this

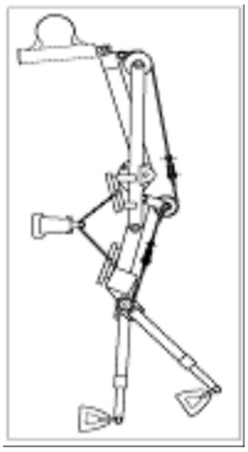

Fig. 1. Overview of the power assisting device

Table 1. Wearable power assist devices

	Power Suit	HARO	HAL	Proposed
Actuator	air	motor	motor	motor
Sensor	skin surface hardness	device load	EMG	EMG
Drawback	large device	large device	small force	1 DOF
Portion	full body	full body	legs	lower back

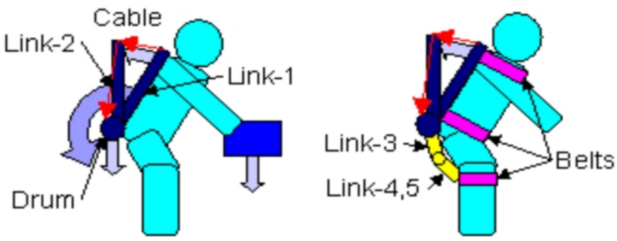

Fig. 2. Schematic diagrams of the proposed power assist mechanism

Fig. 3. A photograph of a person wearing this device

device assist isn't large. They use EMG electrodes to estimate the human force.

The device that we propose is to help daycare in a small room as we often see in Japan. Therefore, the device should assist at least 60kgf and have many DOFs like [3]. But if the device have many motors to make a large force, and many frames to have many DOFs, the device becomes too large, and it won't be used in daily life. So it is reasonable that above devices seems too large or too weak to be used in daily life. However, we focus only on bending (flexion and extension) of a lower back, often injured by carrying heavy load. So the size of this device is not so large as the other above devices. Further, for the portability of the device, we used a DC motor and a battery without any cables to the outside, which means a person wearing this device can walk easily. **Table 1** summarizes the power assist devices and the proposed one.

3. The Power Assist System

A. Outline of this device

Figure 1 shows the draft of links in the device. The metal links are attached to the folders for shoulders, back of a waist, and back of knees. It shows that the regions which touch this device are the shoulders, the back of waist, and the back of knees. There is a cable from the top of the link to the drum that is placed behind a hip. When a DC motor moves, the drum rotates and winds up the cable. So, the upper body rises. And when the DC motor rotates inversely, the drum rotates and releases the cable. So the upper body is moved down. Like these, this device assists a person to pick up or to put down heavy loads.

B. Power assist mechanism

In this section, we show how to assist a person lifting up or putting down heavy loads and how to protect his lower back. The assisting mechanism is shown in the left side of **Fig.2**. When a person is lifting something heavy, erector spinae muscles hold the moment that the mass of upper body leaning forward and the load generate. That's why he gets lumbago. But in this device, giving torque through a cable reduces the force which erector spinae muscles must generate.

From the basic idea, we need only two links like left side of **Fig.2**. But for holding his waist without slipping, another links (Link-3,4,5) are necessary as you see from the right side of **Fig.2**. After all, we made a prototype of the power assist device. **Fig.3** is a picture of a person wearing this device.

C. The structure of this device

Our proposed wearing power assist device consists of five links made of metal and an Aramid fiber cable. Its weight is about 11kg, which is too heavy for women or

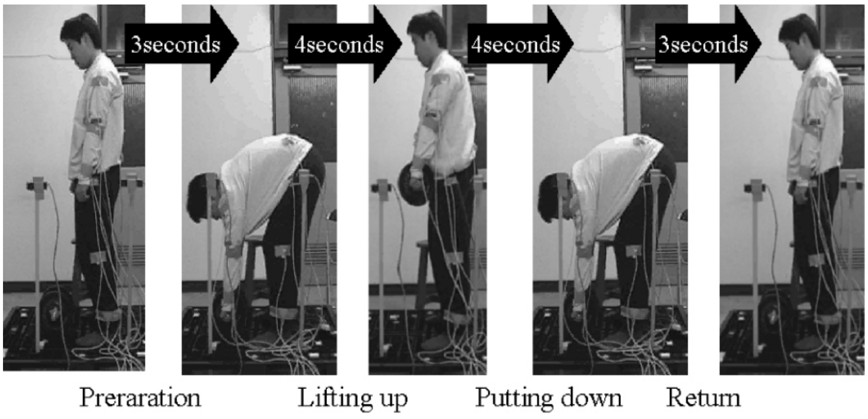

Fig. 4. Measured motion sequence

children. So it needs to be lighter. For the actuator, we used a DC motor which can be controlled easily, and does not make a loud noise. This DC motor is 40W and it made about 50kgf force. We have not discussed about a speed of motor, a necessary torque, and the power that it generate, and so on. These are tasks for future development.

The purpose of this device is to help people with moving a person who can not move in daily life. So, it is important to think of not only how comfort a wearing person feel, but also how a held person feel relieved. A large device made a person feel refusal. A device which lifts a person called "Lifter" made a person feel anxiety. Looking a person wearing this device from the front side, we can not see any parts of the device. Therefore held people do not feel coerced and feel relieved that is held by a person.

In this paper, we analyze human motion in order to achieve control without hands.

4. The Analysis of Lifting Motion

A. The motion which we analyze

In this section, we analyze human motion while lifting heavy load on the floor. A subject lifts up a dumbbell which is 20kg and 10kg, and a cylinder of whose weight people can disregard.

Figure 4 shows a sequence of motion we measure. The subject stands without moving (1 second), moves down to prepare for lifting (3 seconds), lifts up until its height became the same as a waist (4 seconds), waits with holding heavy loads (2 seconds), puts it down to the floor (3 seconds), keeps a position touching the load (2 seconds), and returns to the state before starting (3 seconds). The subject makes three kinds of actions, and repeats the same action twice. So, the subject makes actions twelve times.

In the rehabilitation research field, we have figure out several patterns of lifting motion. Those lifting motions are classified into safety postures for heavy loads and

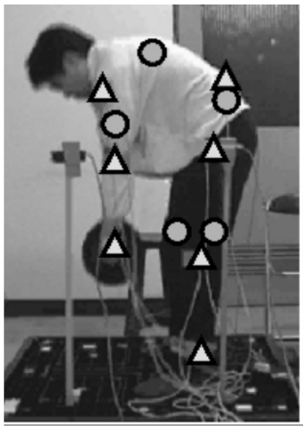

Fig. 5. Sensor location in measuring human motion. The triangular points represent three-dimensional position sensors and the circle points represent EMG electrodes.

dangerous postures. At the safety postures, critical disks at the lumber vertebrae should be supported on the homogeneous pressures at the normal forces, so the back bone should be perpendicular to the ground in order to carry heavy load. The disk connected with each vertebral corporal is made by cartilage. The typical mentions which causes lumbago is shown in **Fig.4**. We know such postures are not good for our health of our body, but sometimes we can not help doing so. For these reasons, we focused on such mentions for the example of the assisting technology.

B. The objects which we measure

In order to control this device, it is necessary to measure the tension in erector spinae muscles. However, because these muscles hide in a deep position, it is impossible to measure the tension directly from a surface. Instead, we can estimate the tension in erector spinae from his posture [9,10]. Nobody can repeat the same actions. So, we find characteristics from the position data processed to angle data.

In addition, it is hard to measure EMG signals of erector spinae muscles because of the same reason. Therefore, we find characteristics from EMG signals of

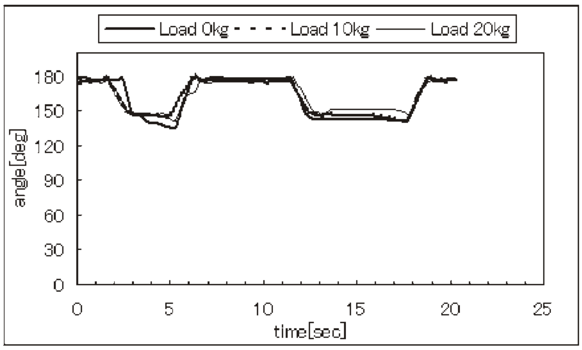

Fig. 6. Variations of angle of knee without wearing this device

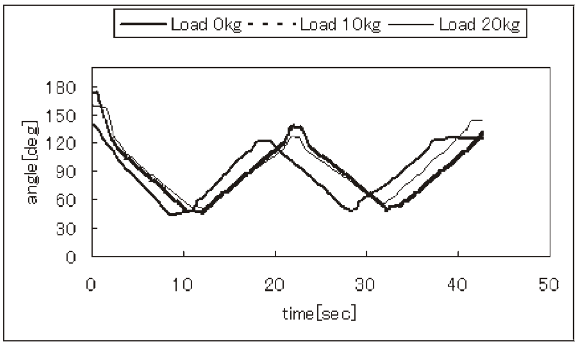

Fig. 7. Variations of angle of waist wearing this device

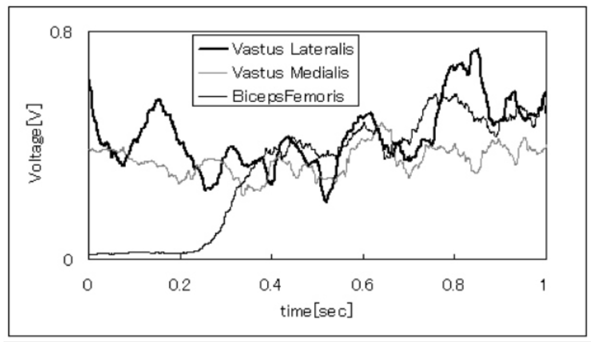

Fig. 8. Variations of EMG signals of thigh muscles at the beginning of lifting up

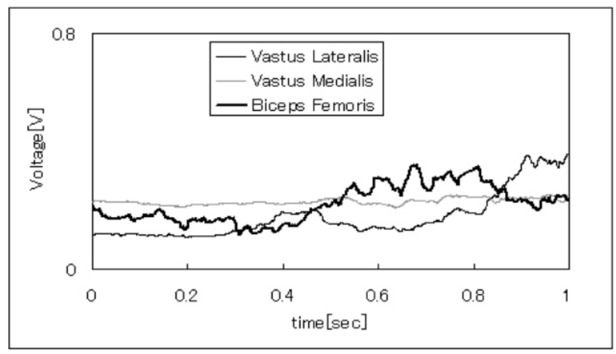

Fig. 9. Variations of EMG signals of thigh muscles at the beginning of putting down

muscles which exists in the surface of the body.

C. The measurement of motions

To analyze human motion, three-dimensional position sensors (Fastrak) and EMG electrodes are used. Every data was taken in a computer. The computer makes a sound which tells a subject to start a next action.

The three-dimensional position sensors are pasted on seven points which measure the positions of heel, waist, back, shoulder, elbow, and wrist. The positions are measured with the rate of 7Hz. EMG electrodes are pasted on eight points, which measure EMG signals of latissimus dorsi muscle, biceps femoris muscle, vastus lateralis muscle, vastus medialis muscles, biceps brachii muscle, triceps brachii muscle, deltoid muscle, and trapezius muscle. The EMG signals are sampled with the rate of 1600Hz. After sampled, they are rectified and smoothed by taking a moving average with the interval of 0.1sec.

Figure 5 shows the distribution of the three-dimensional sensors and the EMG electrodes.

5. Results

A. Results of three-dimensional position sensors

In this section, we analyze the results of the three-dimensional position sensors. Nobody can repeat the same actions. So we convert these position data to angles of joints.

Figure 6 shows variations of an angle of a knee. This figure says that the angles of the joint do not change when the weight of load changes. The angles of the other joints showed the same results.

Next, we compare the result when wearing this device. When wearing the device, the result became incoherent, because of a little difference in the load, which happens to joints. It happens because a subject can not fasten belts similarly. However, the angle of the waist was always the same result. **Fig.7** shows variations of the angle of the waist while wearing this device. From these results we can say that the angle of the waist is useful for control of the device because it has high repeatability.

B. Results of EMG signals

In this section, we analyze the results of EMG signals. In this paper, the purpose is to control the device. So our focus is at the beginning of lifting and putting down. As we mentioned, we measured some places and some characteristics were shown in EMG signals of thigh muscles. **Figs.8** and **9** are the results of EMG signals in muscle thigh.

Figure 8 shows the distribution range of the rectified and smoothed EMG signals of vastus lateralis, vastus medialis and biceps femoris of lifting up an object on a floor with the load of 20kg. This result shows that EMG

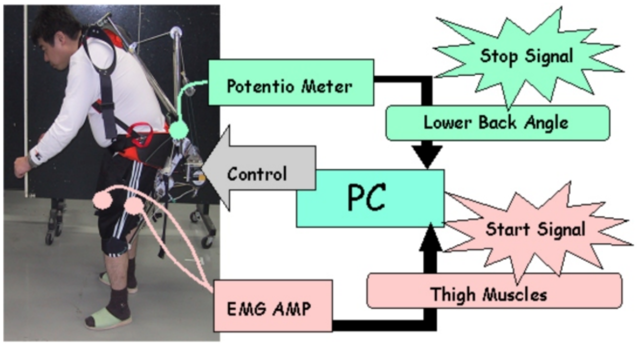

Fig. 10. Schematic diagram of controller for the power assist device for switching the motor

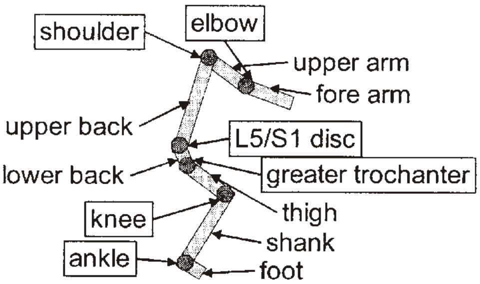

Fig. 12. Seven link planer model of human body

signals of the front thigh muscles(vastus lateralis and vastus medialis) are larger than that of biceps femoris.

Figure 9 shows the distribution range of the rectified and smoothed EMG signals of putting down. This result shows that EMG signals of the back thigh muscles (biceps femoris) are larger than that of front thigh muscles.

C. Lower back angle and thigh EMG signals based control

From the discussion in the previous section, we have developed a controller of the power assist device utilizing the lower back angle and the processed surface EMG signals on the thigh. The objective of the controller is to switch either winding up or down the cable in the device, or stopping the winding. Speed control of the device is not considered here. **Fig.10** illustrates a schematic diagram of the controller. And the flow of cotrol is shown in **Fig.11**.

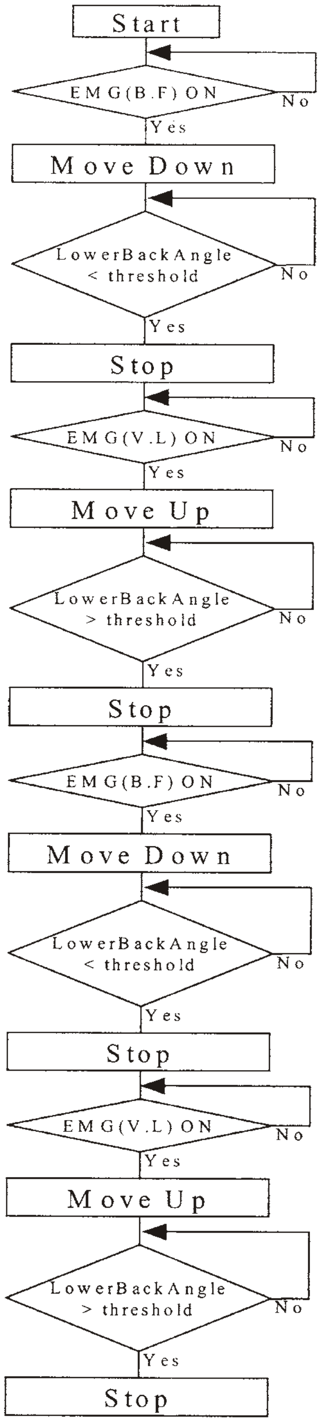

Fig. 11. The flow for control of this device. V.L means vastus lateralis and B.F means biceps femoris.

6. Verification of Results

A. *Verification using human model*

In this section, we model a human body as a two-dimensional seven-link system on a lateral plane and analyze the torque in order to verify above results. The model of a human body is illustrated in **Fig.12**. This model includes seven links: a fore arm, an upper arm, an upper back, a lower back, a thigh, a shank and a foot, and six joints: an elbow, a shoulder, a L5/S1 disc, a greater trochanter, a knee, and an ankle. The link parameters are determined by dimensions of an average male, whose height and weight are 1.80m and 80kg, respectively. The right of **Fig.13** illustrates a human model with the power assist device.

Since the human body is a closed system, the external forces or torques distributed into the links of human body. Therefore the power assist device shares the

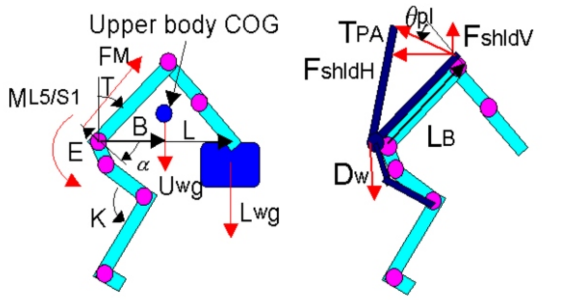

Fig. 13. Human model with and without the power assist device

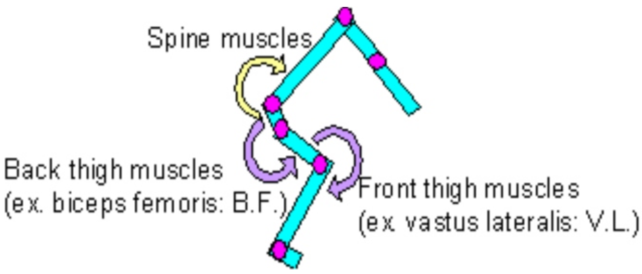

Fig. 14. Schematic diagram of representative muscles in lower body

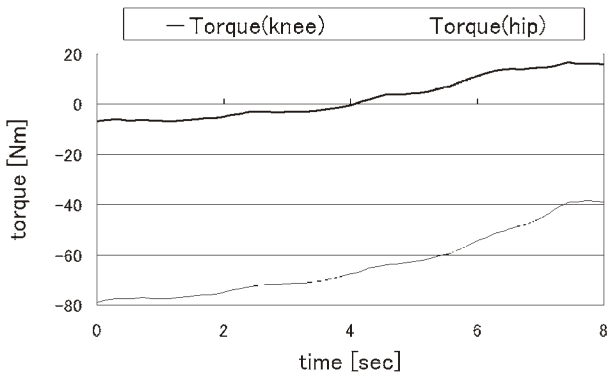

Fig. 15. Changes of expected torque of knee and hip joints while a subject is lifting up heavy loads

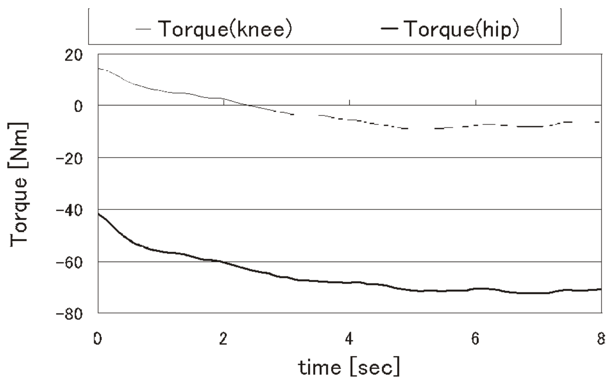

Fig. 16. Changes of expected torque of knee and hip joints while a subject is putting down heavy loads

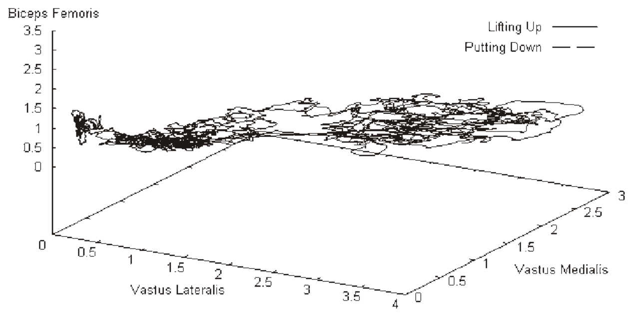

Fig. 17. The result of EMG signals for each motion which needs assists without wearing Power Assisting device. A subject moved with 20kg weight in his hands.

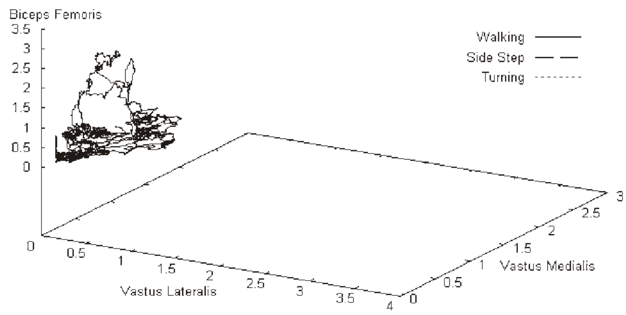

Fig. 18. The result of EMG signals for each motion which doesn't need assists without wearing Power Assisting device. A subject moved with 20kg weight in his hands.

internal forces or torques on the L5/S1 disk and greater trochanter. **Fig.14** illustrates a schematic diagram of representative muscles in a lower body. Biceps femoris connect a lower back link and a thigh link. Similarly, vastus laterralis and vastus medialis connect the thigh link and a shank link. Therefore we can say that EMG signals of the biceps femoris are related to torque of hip joint, and EMG signals of vastus laterralis and vastus medialis are related to torque of a knee joint. Accordingly we estimated torque of the knee joint and hip joint.

Figure 15 shows the changes of estimated torque of the knee and the hip joints while lifting up the 20kg load wearing the device. In this figure, the absolute value of torque of the knee is getting larger while the absolute value of torque of the hip is getting smaller. This result shows that the tension of vastus laterralis and vastus medialis become larger, which means the EMG signals of these muscles become larger.

Figure 16 shows the changes of estimated torque of the knee and hip joints while putting down the 20kg load wearing the device. On the contrary, the absolute value of torque of the hip is getting larger while the absolute value of torque of the knee is getting smaller in this figure. This result shows that the tension of biceps femoris becomes larger, which means the EMG signals of these muscles become larger.

These results suggest that the result of **Figs.8** and **9** matches well to the human model and our proposed controller shown in **Figs.10** and **11** will move correctly.

B. Recognition of lifting and daily life motions

From the viewpoint of safety, it is more important that this device does not move suddenly in daily life than it moves voluntary. In this section, to verify our proposed controller, we have an experiment which shows that the EMG signals can be discriminated, which implies the device move only when a wearing person needs the assist.

EMG electrodes are pasted on vastus lateralis, vastus medialis and biceps femoris. A subject takes the following actions with this device. These actions are thought to occur in the case that a person transfer from a bed to a wheelchair.

1) *Actions when a person needs assistance.*
   a) Lifting up heavy loads.
   b) Putting down heavy loads.
2) *Actions when the device must not move.*
   c) Walking.
   d) Side stepping.
   e) Left turning.

The subject takes above five actions with wearing this device. Heavy loads are dumbbells of 20kg and a cylinder of whose weight people can disregard.

Figures 17 and **18** show the rectified and smoothed EMG signals of the front and back thigh muscles for five motions: picking up, putting down, walking, side stepping and left turning. The motions of picking up and putting down are spread into horizontally (see **Fig.17**), while the other motions are distributed vertically (see **Fig.18**). It seems that the motions of picking up and putting down can be recognized by the feature values of a short sequence of the processed EMG signals, with appropriate thresholds.

C. An experiment to verify our proposed controller

From above all results, we have an experiment our proposed controller. As we show **Fig.10**, a subject wears this device and pastes EMG electrodes on vastus lateralis, vastus medialis and biceps femoris. In the back of the device, a potentio meter, which measures a low back angle, are set in the device. Thresholds of EMG signals and low back angle are decided manually from the results of **Figs.7**, **8**, and **9**.

Figure 7 showed that the range of angle is between 60 and 120 . So if the lower back angle exceeds the range while moving, the controller makes this device stop moving. **Figs.8** and **9** showed the relations with EMG signals. We set the threshold of EMG signals, which shows the beginning of motions. The threshold of lifting up is set as 0.6V, EMG signals of vastus medialis exceeds the threshold at the beginning of lifting up (t 0) as shown in **Fig.8**. The threshold of putting down is set as 0.3V, EMG signals of biceps femoris exceeds the threshold at the beginning of putting down (t 0.5).

The experiment was carried out as following. The device begins releasing the cable and stops after lower back angle exceeds the threshold. The subject begins picking up heavy loads. Then the device begins winding up because the subject begins picking up and the EMG signal of biceps femoris exceeds the threshold. At last, the device stops after the subject stands.

This experiments showed that our proposed controller made it possible to switch without using hands.

7. Conclusion

In this paper, we proposed the power assist device which prevents from lumbago. And after the analysis of human motions, we showed that we can control this device utilizing EMG signals of three thigh muscles and the low back angle.

Also, we analyzed EMG signals of the three thigh muscles not only signals when lifting or putting down heavy loads, but also signals in daily life motions. The result showed that our proposed controller does not interfere with daily life.

Finally, we had the experiment to control this device utilizing EMG signals and the low back angle. We have verified that we can control this device as a wearing person wants it to do if we set exact thresholds.

From now on, we are going to discuss about how to make thresholds automatically utilizing artificial neural networks et al. Besides, an embedded controller will be designed in order to control without notebook PC for walk around more easily while wearing.

References:

[1] T. Inoue, and N. Yamazaki, "Physical loads while using moving assisting devices," Journal of the Society of Biomechanisms, Vol.25, No.3, pp. 123-129, 2001 (in Japanese).

[2] J. Main, "Exoskeletons for Human Performance Augmentation", http://www.darpa.mil/dso/thrust/matdev/ehpa.htm.

[3] K. Yamamoto, K. Hyodo, M. Ishii, and T. Matsuo, "Development of Power Assisting Suit for Assisting Nurse Labor", Transactions of the Japan Society of Mechanical Engineers, Vol.67, No.657, pp. 1499-1506, 2001 (in Japanese).

[4] K. Yamamoto, K. Hyodo, M. Ishii, T. Matsuo, and K. Sawada, "Load Cell and Rotary Actuator using Pressure Cuff", FLUCOM2000, 2000.

[5] S. Morishita, T. Tanaka, K. Yamafuji, and N. Kanamori, "Improvement of Maneuverability of the Man-Machine System for Wearable Nursing Robots", Journal of Robotics and Mechatronics, Vol.11, No.6, pp. 461- 467, 1999.

[6] T. Aoki, and K. Taguchi, "A Study of Human-Assist-Robot -Development of a Prototype Robot for Nursing Use-", Journal of the Robotics Society of Japan, Vol.21, No.2, pp. 157-163, 2003 (in Japanese).

[7] S. Lee, and Y. Sankai, "Power Assist Control for Walking Aid with HAL-3 Based on EMG and Impedance Adjustment around Knee Joint ", 2002 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS2002), pp. 1499-1504, 2002.

[8] H. Kawamoto, and Y. Sankai, "Power Assist System HAL-3 for Gait Disorder Person", LNCS 2398, p. 196, 2002.

[9] D.B. Chaffin, G.B.J. Andersson, and B.J. Martin, "Occupational biomechanics third edition", Wiley-interscience, 1999.

[10] K. Naruse, S. Kawai, H. Yokoi, and Y. Kakazu, "Design of compact

and lightweight wearable power assist device," ASME International Mechanical Engineering Congress & Exposion, 2003.

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The Japan Society of Mechanical Engineers (JSME)
The Japanese Society of Instrumentation and Control Engineers (SICE)
The Robotics Society of Japan (RSJ)