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Fuzzy Control of a New Tendon-Driven Exoskeletal Power Assistive Device

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Abstract— **This paper proposes a tendon-driven exoskeletal power assistive device to reduce some problems of the existing exoskeletal power assistive equipment. In addition, this paper suggests a caster walker carrying heavy peripheral devices and maintaining stable balance of the user at the same time. A muscle fiber expansion signal is used to control this device in order to compensate for the delay time of motors and perform an easy assistance by sensing the user's action in advance. The muscle fiber expansion signal has the characteristics that the signal is ahead of action and in proportion to joint torque. A fuzzy control method is applied to control the proposed exoskeletal assistive device. This paper also describes a number of action tests such as sitting, standing, and walking. The experimental results were quantitatively evaluated by comparing the EMG signal before and after wearing of the proposed exoskeletal assistive device.**

Fig. 1. Pictures of the tendon-driven exoskeletal power assistive device and caster walker

I. INTRODUCTION

An exoskeletal power assistive device is a type of wearing robot using the synchronization between human and robot. This EPAD (Exoskeletal Power Assistive Device) has been largely investigated from the rehabilitation equipment for muscle disease patients to the muscle power amplifying device for the soldier who carries heavy military equipment[1]. The EPAD uses various driving methods. The servo motors are applied as HAL (Hybrid Assistive Leg)[2-4], and a hydraulic driving unit is used for the BLEEX (Berkeley Lower Extremity Exoskeleton)[1]. Yamamoto *et al.* developed an exoskeleton for nurses using a pneumatic driver[5]. Pratt and Herr suggested an EPAD for the knee and ankle using a SEA (Series Elastic Actuator)[6-7].

Watanabe and Sankai *et al.* estimate the joint torque using the property that an EMG (Electromyography) signal is measured in advance before the human motion[2-4,8]. Rosen presents an assistive method for an arm using a muscle model[9-10]. Yamamoto measures the hardness of muscle when the muscle contracts using a load cell, and applies it to the control of his exoskeleton[5].

The major issue in the field of the EPAD may be how much power is to be assisted. In practice, however, the easiness of use of an EPAD especially for the elderly people and patients, who suffer from weakening of the pelvic limb muscle, is of more importance than anything else. The present device has some problems in actual application for such people. First, an EPAD needs to be smaller and lighter. Although an EPAD can support its own weight while it is controlled, the weight is very important because the user wears the EPAD while the power is turned off. In addition, the user who wears a large size of the EPAD can't sit in a chair, which has an armrest, and can't enter a small space such as a bathroom. Second, the easy use of the sensors is required. Although the EMG sensor presents a good performance, this method also presents an inconvenience due to the direct attachment of sensors on the body.

This paper proposes a new type of EPAD, a tendon-driven exoskeletal assistive device (TEAD), in order to solve some problems existing in the current EPAD. In order to minimize the weight and volume, a controller, battery, actuators and drivers are removed. However, a caster walker, which can be moved by pushing, stores all heavy peripheral equipments. The weight of a wearable exoskeleton can be reduced to less than 3Kg through these adjustments. The mechanical power of the caster walker is transmitted to the wearable exoskeleton using a tendon-driven method. Fig. 1 presents the wearable exoskeleton and caster walker proposed in this paper. In addition, a detachable power transmission unit is applied to support easy wearing. In the case of the existing EPAD, which causes resistance to the user's action when the power is turned off, the proposed TEAD does not present any resistance if the power transmission unit is removed.

This paper proposes and applies a muscle fiber expansion signal to calculate the joint torque. Yamamoto introduced a muscle hardness sensor in 2000[5]. He mentioned that the muscle hardness sensor uses the property that muscle is hardened when muscle contracts, and is in proportion to joint

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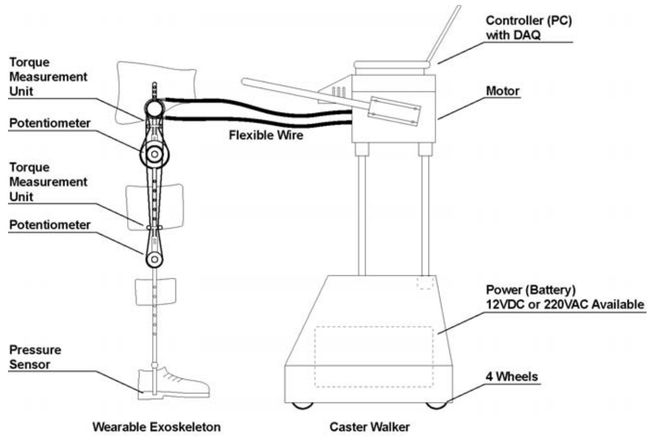

Fig. 2. Schematic plot of the Tendon-driven Exoskeletal Assistive Device

torque[5]. However, the muscle hardness sensor is also directly attached on the body like the EMG sensor, and is highly priced due to the use of load cells. In order to solve these problems, this paper proposes an MFE (Muscle Fiber Expansion) sensor using an air pressure plate and low priced pneumatic sensor. The proposed MFE sensor measures changes in the air pressure in the plate, where the changes are generated by the expansion of muscle fiber when the muscle contracts. The proposed sensor does not need to be directly attached on the user's body, and does not have complicated signal processing differed from an EMG sensor and muscle hardness sensor. In addition, it is not necessary to consider the attaching point whenever it is used because this sensor is installed to the wearable exoskeleton.

This paper uses a fuzzy control method to control the proposed TEAD. Pratt and Herr used a feedback control method using PD controller in order to control a SEA[6-7]. Sankai used an open loop control method for the estimated joint torque, which was estimated by real-time, through a phase-sequence method and EMG[2-4]. Rosen *et al.* introduced a neural network theory[9-10]. This paper computes joint torque in real-time using MFE sensors, and controls using a fuzzy control method.

II. TENDON-DRIVEN EXOSKELETAL ASSISTIVE DEVICE

This paper proposes a tendon-driven exoskeletal assistive device in order to minimize the weight and volume which are demerits of the existing EPAD. The designed equipment consists of a wearable exoskeleton and caster walker as shown in Fig. 2. In order to reduce the weight applied to the user, most peripheral equipments except for sensors are installed on the caster walker. A double layered wire is linked to transfer the power. Pulling two wires wound around the pulley of the wearable exoskeleton, the power is transferred.

However, there are some inconveniences when a user wears or divests the device because the exoskeletal assistive device and caster walker are constrained by the wire. The user may want active assistance or move freely under a certain passive state according to the given conditions. Thus, a detachable power transmission unit is installed to the TEAD.

Fig. 3. Practical usages of the TEAD

This power transmission unit acts as a clutch, playing an active assistance role in the case where the power transmission unit is installed on the wearable exo- skeleton. Conversely, it is possible to freely move when the power transmission unit is removed. Thus, the user can wear and divest the wearable exoskeleton without any difficulties by removing the power transmission unit while the power is turned off. This is a great merit when compared to the state where the movement is limited by the resistance of drivers or gears while the power is turned off in the existing EPAD.

A user who wears the existing EPAD cannot sit in a chair that has an armrest, and cannot enter a small space, such as a toilet due to its size. The proposed TEAD can make it easy to sit in the chair as presented in Fig. 3 because it has no extra volume of peripheral devices, which also makes it possible to use a toilet.

A potentiometer is installed at the wearable exoskeleton in order to measure an absolute angle for each joint. In addition, eight MFE sensors are attached to grasp the intention of the user's movement and estimate joint torques. A PC, four motors, drivers, and power supply are installed to the caster walker including a data acquisition board. The power source can be selectively applied either a 12 V DC battery or 220V AC. In addition, mechanical angle limiters for joints are installed at the wearable exoskeleton, and an emergency switch is installed on the caster walker in order to protect the user from the unlikely event of a potential malfunction.

III. MUSCLE FIBER EXPANSION SENSOR

A muscle fiber expansion signal is used to calculate joint torques. This MFE signal is the measurement of the swelled muscle at the contraction of the muscle. Fig. 4 presents the principle of the MFE sensor. An MFE sensor attached inside of thigh braces is easy and simple to use compared to EMG sensors which are directly attached at the exact points of muscle before the use of an EPAD. In addition, this sensor is practical due to the use of a cheap pneumatic sensor when compared to a muscle hardness sensor which uses a load cell. Fig. 5 presents the location of a MFE sensor.

A joint requires a link with two more muscles to guarantee free movement in both directions because muscular power is generated along the direction of muscle contraction. Sankai uses a differential amplification method for the signal which is measured at the front and rear of the thigh in order to calculate virtual torque using EMG signals[2-4]. This paper also uses the differential value between the MFE sensors in order to estimate the torques of the hip and knee joints. The torques of the hip and knee joints can be estimated using Eq. (1) as follows.

$$\tau_{Hip} = k_1(MFE_{AL} - s_1 \times MFE_{GM} - Bias_1) \quad (1)$$
$$\tau_{Knee} = k_2(MFE_{RF} - s_2 \times MFE_{BF} - Bias_2)$$

where the symbols are defined as follows.

- *MFE* = Muscle Fiber Expansion Signal
- *Bias* = Bias Signal of the Sensor
- *AL* = Adductor Longus Muscle
- *GM* = Gluteus Maximus Muscle
- *RF* = Rectus Femoris Muscle
- *BF* = Biceps Femoris Muscle

The k_1 and k_2 are the parameters to decide the scale of joint torque and the s_1 and s_2 are the parameters used to adjust the sensor signals with the same ratio. Each muscle is represented in Fig. 5.

The parameters used in the MFE sensor present different values for the different individuals. The parameters even show different values according to the muscle fatigue for a single person. Thus, the two initialized actions are configured under the state of comfortable standing and sitting, respectively, in order to decide the parameter. In the two actions, the MFE sensor shows a different value, and all parameters can be initialized using the measured information due to the fact that all joint torques are assumed as 0 for each state. In addition, the measured values under the comfortable standing are assumed as the bias values. Fig. 6 presents an algorithm used in the parameter initialization process, where $\tau_{Maximum\ Setting}$ is a constant which converts the measured sensor signal to joint torques.

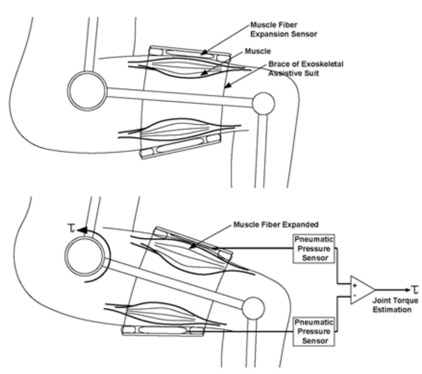

Fig. 4. Principle of measuring the muscle fiber expansion signal

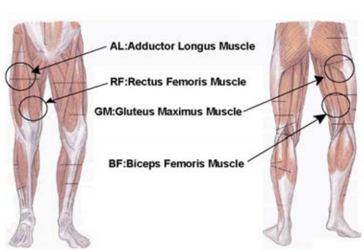

Fig. 5. Sensing points

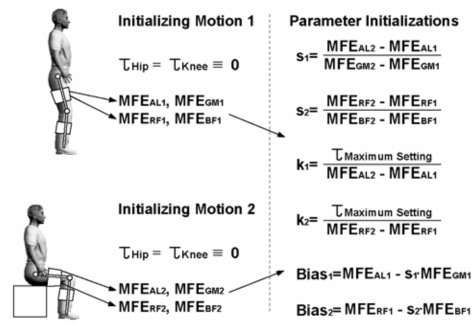

Fig. 6. Parameter initializations

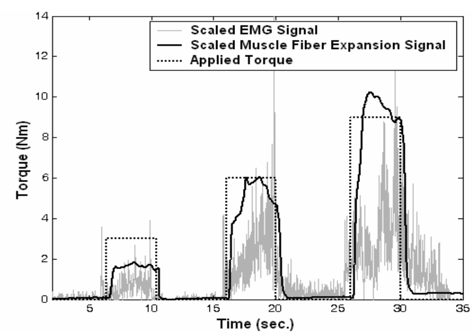

Fig. 7. Comparison of the EMG signal and muscle fiber expansion signal

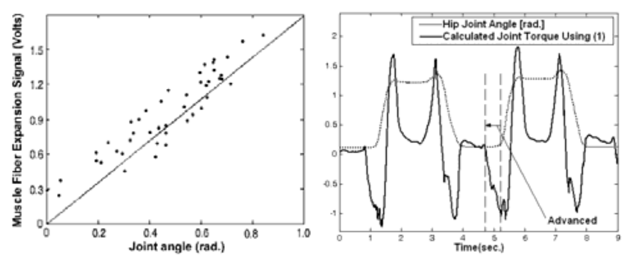

Fig. 8. Proportionality between the MFE signal and the joint torque (Left) and Hip joint angle and estimated torque (Right); the section marked as "Advanced" represents that the signal preceded the joint action

The MFE sensor is in proportion to the joint torque. Fig. 7 presents the measurement of MFE signal by resisting the force which was applied to the tester where the force was produced by applying a number of constant input currents to the motor of the exoskeletal assistive device. As a result, the MFE sensor presents very uniform value and less noise though both EMG and MFE signals are in proportion to the joint torque.

The left figure in Fig. 8 presents the measurement data that the MFE signal at different joint angles during the lift up of the thigh presents a proportional relationship. The hip joint requires a large torque as the angle of thigh increases and the MFE signal is proportional to it.

The MFE signal acts in advance before movement. The right figure in Fig. 8 presents the comparison between the hip joint and the calculated joint torque for the action of sitting and standing. The section marked as "Advanced" presents the advance time for a movement. In addition, the MFE signal showed a uniformly repeated value while the action was repeated.

IV. FUZZY CONTROL METHOD

A fuzzy control method has many degrees of freedom in the design of a controller, and is proper to the proposed TEAD because it is possible to configure an intuitive controller for various conditions.

The movement of muscle consists of three modes: an active mode, passive mode, and free mode. Muscular power is generated by the muscle contraction in an active mode, and is generated by the muscle relaxation in a passive mode[11]. Conversely, a muscle can be contracted or relaxed in a free mode, and there is no generation of the muscle power in this mode[11]. The EMG or MFE signal cannot be exactly measured in this free mode, and consequently it becomes an obstacle in the control of an exoskeletal assistive device. Sankai produced natural frequencies by assuming the calf in a free mode acts as a pendulum in order to solve this problem, and proposed a natural frequency method to make a free movement of the calf according to the measured natural frequency[12]. This paper attempts to solve this problem using the joint angular velocity with the calculated joint torque as an input to a fuzzy controller. Because the joint torque is not exactly calculated using the MFE signal in the free mode, the exoskeletal assistive device will disturb the user's movement. Thus, in the case, when the calculated joint torque is a small value while joint is moving, the motor is driven to the same direction to the joint angular velocity in order to remove the resistance of motors or gears.

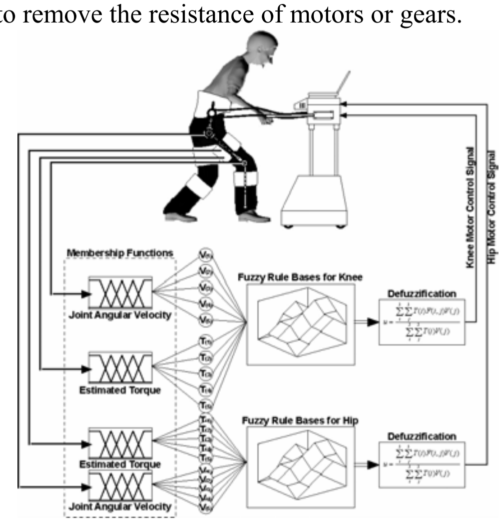

Fig. 9. Schematic plot of overall control system

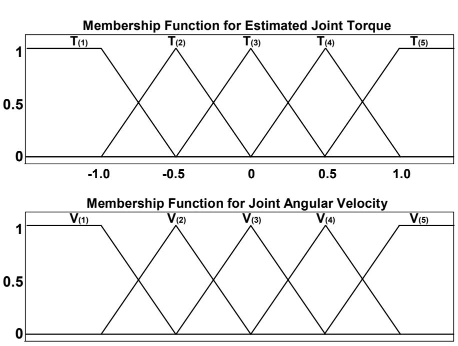

Fig. 10. Fuzzy membership functions

Fig. 9 presents the entire configuration of the control structure. In order to control the motor which drives the hip and knee joints, each fuzzy membership function, fuzzy rules, and defuzzification function are configured.

A triangle function is used for fuzzy membership function. In order to use the calculated joint torque using Eq. (1) and joint angular velocity as input variables, a scaling from -1 to 1 is applied to configure values in this region. Fig. 10 presents the fuzzy membership functions.

A number of rules are configured to set the fuzzy rules. If the joint torque calculated using the MFE signal is small and the joint angular velocity is large, the motor is driven through the joint angular velocity because the muscle is moving in a free mode. Conversely, if the joint angular velocity is small and joint torque is large, the motor is driven according to the joint torque. If the joint angular velocity and joint torque present the same direction, the input signal to the motor is to be increased, otherwise decreased in the case of the reverse direction. By following these rules, the fuzzy rules are configured as shown in Fig. 11, where the x-axis represents membership variables of the joint torque. The y-axis represents membership variables of the joint angular velocity, and z-axis represents all controller outputs for each state.

The controller output is defined as a matrix through the membership function and fuzzy rules. A defuzzification function which uses an interpolation method is applied to convert the matrix to a scalar value. The applied defuzzification function can be expressed as follows.

$$u = \frac{\sum_{i}^{5}\sum_{j}^{5} T(i)F(i,j)V(j)}{\sum_{i}^{5}\sum_{j}^{5} T(i)V(j)} \qquad (2)$$

where T(i) and V(i) are the membership variables of the joint torque and velocity respectively, u is the defuzzified controller output, and F(i,j) is the controller output which corresponds to the z-axis as presented in Fig. 11.

V. EXPERIMENT AND ANALYSIS

The tendon-driven exoskeletal power assistive device and fuzzy control method were applied to the experiment of sitting, standing, and walking. The experiments were performed to a normal person and the EMG signal was measured to quantitively verify the assistant effect.

Fig. 13 presents pictures of the experiment of sitting and standing. Fig. 12 presents the knee joint information during the sitting and standing experiment where the upper graph shows the angle of the knee joint and the second graph presents the MFE signals (dotted and dashed line) and calculated torque (thick continuous line). The third one presents the joint angular velocity and the lower figure means the output of the fuzzy controller. In these figures, the vertically drawn continuous line means that the signal entered to the motor before the joint moved.

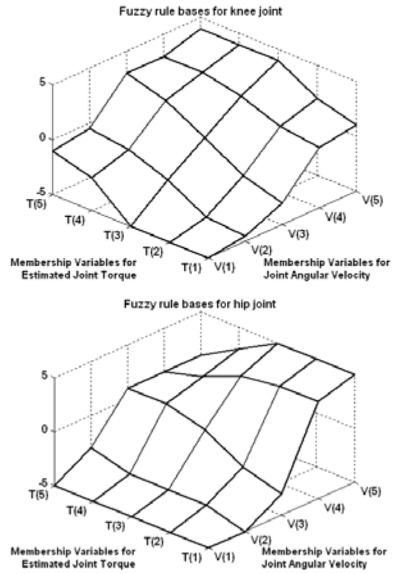

Fig. 11. Fuzzy rule bases

Because the EMG signal presents the scale of the muscular power[13-14], an EMG sensor was used to quantitively evaluate the assistant effect. Fig. 14 presents the comparison of the EMG signals before and after wearing the exoskeletal assistive device for sitting and standing actions. Table 1 shows the peak values of each EMG signal presented in Fig. 14 where the muscular power decreased about 27% due to wearing the TEAD.

Fig. 15 presents the walking experiment at a steady speed without changing the direction. Fig. 16 presents the knee joint data during the experiment. In the section of vertically drawn long lines, the calculated joint torque was small and the absolute value of joint angular velocity was large where the muscle was in the free mode. Thus, the output of the controller presented in the fourth figure was decided according to the joint angular velocity in this section.

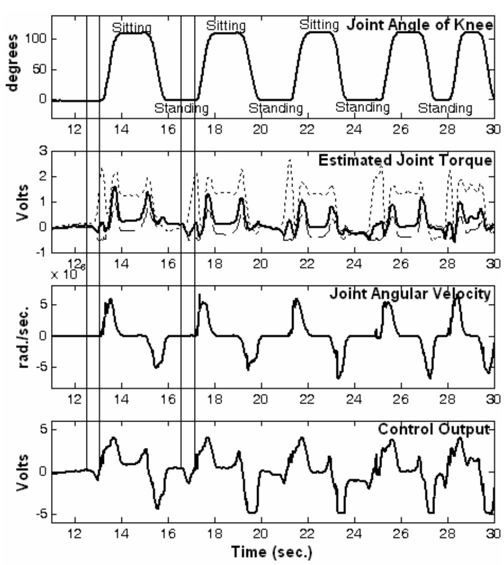

Fig. 12. Data of knee joint at sitting and standing experiments

Fig. 13. Picture of sitting and standing experiments

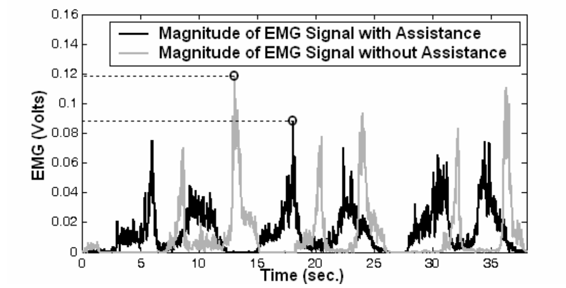

Fig. 14. Comparison of the EMG signal

TABLE I
PEAK VALUE OF EMG SIGNAL AT THE SITTING AND STANDING MOTION

without the Exoskeletal Assistive Device [V]	with the Exoskeletal Assistive Device [V]	Effect of Assist [%]
0.118	0.087	26.7

Fig. 15. Picture of walking experiments

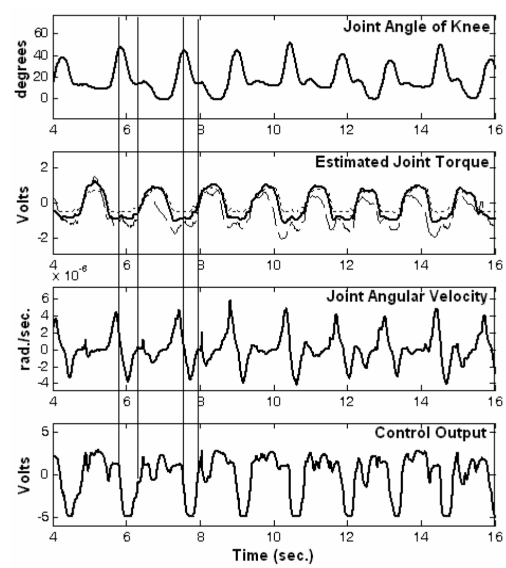

Fig. 16. Data of knee joint at walking experiments

VI. SUMMARY

This study proposed a tendon-driven exoskeletal assistive device which consists of a wearable exoskeleton and caster walker to solve problems currently existing in the exoskeletal power assistive device. The proposed device is convenient by reducing the weight of a wearable exoskeleton less than 3Kg, and minimizing its volume. Instead of wearable exoskeleton, a caster walker carries heavy peripheral devices.

A fuzzy control method was used to control the proposed TEAD. The experimental result was quantitively analyzed by comparing the EMG signal. As a result, the assistant effect of the muscular power was about 27%. The fuzzy control method used in this paper decides the output based on the signal from MFE sensors and joint angular velocity. Thus, it is compatible for an arbitrary motion as well as sitting, standing, and walking motions.

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