Design and Control of a Power-Assist System for Pedal Operation

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***Abstract*—A driver operates the accelerattion pedal by perceiving reaction force in driving a car. In pedal design, it is necessary to design a reaction force characteristic that can improve the pedal operation feeling and the car acceleration feeling. In order to investigate the reaction force characteristic of the acceleration pedal, an ankle power-assist system which is able to assist the pedal operation of the car driver based on electromyographic (EMG) signals is developed. The effectiveness of the proposed power-assist system was evaluated under three kinds of driving postures.[1]**

***Index Terms*—Ankle power-assist, EMG based control, Automobile**

I. INTRODUCTION

A driver applies operating force necessary to operate an accelerator pedal by perceiving reaction force during driving a car. Therefore, it is important to design an acceleration pedal to make a proper reaction force characteristic considering excellent pedal operability. A design method of pedal reaction force based on sensory characteristics of human beings by measuring and modeling reaction force perception characteristics during pedal operation was reported [1]-[3]. In the driving environment of a car, since the pedal operation by a driver is influenced by acceleration, a gap between the estimated acceleration caused by the pedal operation and the actually generated acceleration is generated. Improvement in operability and comfortability of the pedal operation can be expected by designing an acceleration pedal which can obtain the expected pedal reaction force and the estimated car acceleration are generated to compensate for the gap. In order to complement the pedal operating force, an ankle power-assist system is proposed in this paper. Some ankle power-assist systems have been developed for rehabilitation or preventing the drop-foot gait [4]-[6]. In this paper, the ankle power-assist system for pedal operation is designed and controlled to assist the pedal operation of a car driver. The proposed ankle power-assist system measures the electromyographic (EMG) signals of the driver's lower-limb muscles and transmits the torque of the actuator with a wire to generate an arbitrary operating force to assist the pedal operation according to the driver's intention. Using the EMG signal as the control signal, time delay can be reduced and smooth operation can be achieved [7]. The effectiveness of the proposed power-assist system for pedal operation has been evaluated by performing experiments.

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II. DESIGN AND CONTROL OF THE SYSTEM

A. Construction of the Device

Fig. 1 shows the system configuration of the proposed assist device. This device has one degree of freedom on an ankle joint, and consists of a frame from a shin to a forefoot, a band connecting the frame and a wearer, a DC motor (RH-8D-6006) generating a torque, and a wire to transmit the generated torque. In addition, this device is equipped with two rotary encoders (MEH-20-3600-PC) for measuring the knee and the ankle joint angles, an input box (JB-620J) for measuring surface EMG (Electromyogram) signals, an amplifier (MEG-6108) for multipurpose measurement, a force sensor (USL06-H12-500N-AP) to measure the force caused by the motion difference between the robot and the driver being, and two strain gauges to measure the tension on the wire.

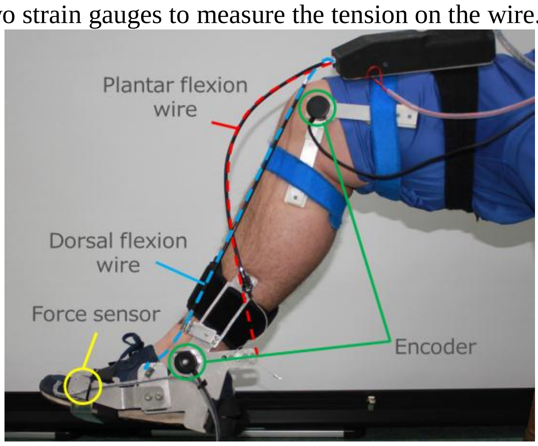

Figure 1. Configuration of the device

In order to assist the operation of the accelerator pedal of a car, several specifications are required in this

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apparatus. First of all, with regard to the output, the maximum assist torque for the ankle joint during operation of the accelerator pedal is about 10 Nm. This device is designed to assist 1/5 of driver's ankle torque. Therefore, this device is equipped with a DC motor with a maximum output torque of 2.7 Nm. Furthermore, since it is necessary not to hinder the pedal operation with this device, the weight of the frame is reduced by using aluminum. Since the interval between the accelerator pedal and the brake is limited and there is not enough space on the pedal top, the device needs to be small near the ankle joint. Therefore, in the proposed system, a DC motor was attached to the thigh and the torque was transmitted by the wire to generate an assist torque for the ankle joint.

B. Control of the Device

Basically, the proposed power-assist system is activated based on EMG signals. Since the EMG signals of the active and cooperating muscles related to the plantar flexion/dorsiflexion are measured, the ankle joint torque τ_{ankle} can be estimated based on the EMG signals and regarded as the torque around the ankle joint of the driver for the pedal operation. The assist torque, which is obtained by multiplying the ankle joint estimated torque τ_{ankle} by the assist ratio α, is expressed as follows:

$$\tau_{assist} = \alpha \times \tau_{ankle} \tag{1}$$

This torque is output from the DC motor, and power-assist is performed by transmitting the torque with the wire. In the initial stage of the stepping motion, it is possible to step down without activating the muscles by the effect of gravity. In this case, when the amount of the EMG signal is small, force sensor based control is applied. In addition, the wire is always tensioned to ensure that the wire does not loosen. Assuming that the assist torque calculated based on the EMG signal is τ_{assist}, the torque calculated by the force sensor base is τ_{force}, and the torque for the tension control is τ_{tention}, the output torque τ_{motor} can be obtained with the following equation.

$$\tau_{motor} = f(x)\tau_{assist} + \left(1 - f(x)\right)\tau_{force} + \tau_{tension} \tag{2}$$

Here, $f(x)$ is a sigmoid function, which is determined from the waveform of the EMG signal at the time of rest and underlying flexion and x is a value obtained by summing values obtained by RMS processing of EMG signals of the tibialis anterior muscle, peroneus longus muscle, gastrocnemius muscle and soleus muscle.

C. Motion Estimation Based on EMG

The proposed device uses the EMG signals to predict the driver's motion intention for the pedal operation. Measurement points for EMG signals are gastrocnemius and soleus muscles, which are protagonistic muscles of the ankle plantar flexion, and peroneus longus muscle which is a synergistic muscle. For the dorsiflexion operation, motion intention is estimated based on the EMG signals of the tibialis anterior muscle which is the protagonistic muscle. Fig. 2 shows the location of the electrodes for EMG signals.

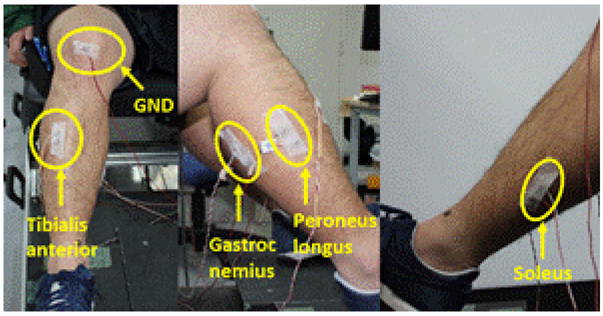

Figure 2. Measurement points for EMG signals

In order to use these EMG signals as control signals, the feature is extracted with RMS processing. The EMG signal after RMS processing is $v_{\text{rms,j}}$, and τ_{ankle} is calculated with the following equation:

$$\tau_{ankle} = \begin{pmatrix} w_{a1} & w_{a2} & w_{a3} & w_{a4} \end{pmatrix} \begin{pmatrix} v_{rms,1} \\ v_{rms,2} \\ v_{rms,3} \\ v_{rms,4} \end{pmatrix} \tag{3}$$

Here, w is the initial weight value. In consideration of contribution degree of the EMG signal of each muscle in plantar flexion/dorsiflexion operation, the initial weight value was defined as shown in Table 1. For the sake of convenience in this study, the sign of the weight value is positive for plantar flexion motion, and negative for dorsiflexion motion.

TABLE I. INITIAL WEIGHT VALUES

ch	Muscle;j	Motion	$w_{a,j}$
1	Tibialis anterior	Dorsiflexion	-1.0
2	Peroneus longus	Plantar flexion	0.2
3	Gastrocnemius	Plantar flexion	0.3
4	Soleus	Plantar flexion	0.5

D. Parameter Modification with Fuzzy-neuro Modifier

The activity level of the EMG signal is affected by individual differences and physical condition of a person. Also, among the muscles to be measured, the gastrocnemius muscle is a bi-articular muscle straddling the two joints of the knee and ankle, and the signal changes according to the change in the knee joint angle, so the relationship between the magnitude of the EMG signal and the torque of the joint is changed according to the knee joint angle, although it is difficult to figure out the relationship between them accurately [8]. Particularly in driving a car, it is necessary to compensate for the relationship between various driving attitudes and EMG signals caused by differences in physique and type of a driver. In the proposed system, a fuzzy-neuro modifier that is a combination of fuzzy inference and artificial neural network is used to learn the relationship between them [9]-[11]. The fuzzy-neuro modifier modifies the initial weight values in eq. (3) by multiplying the coefficients (i.e., the output of the modifier). Fig. 3 shows the model of the fuzzy-neuro modifier used in this study. The weight value of the fuzzy-neuro modifier is updated with the error back propagation leaning method. In the error back propagation leaning method, the weight value is updated so as to minimize the error function *E* obtained from the toe portion operation error target value ($y_d = 0$) and the value of the toe portion force sensor shown in Fig. 4. Therefore, the learning is performed to minimize the motion error between the assist device and the driver's foot at the time of depression operation.

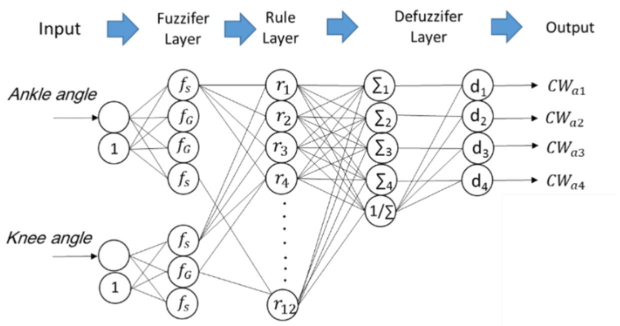

Figure 3. Fuzzy-neuro modifier

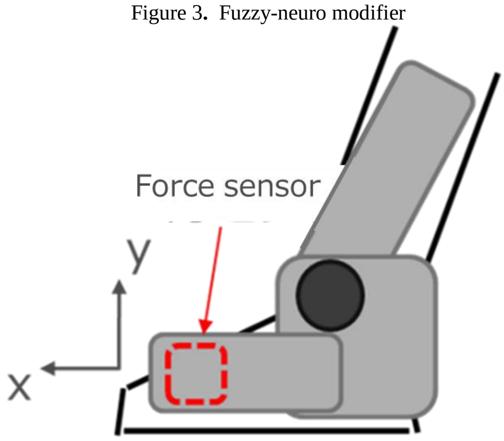

Figure 3. Mounting position of the force sensor

III. Experiment

In order to confirm the effectiveness of the proposed power-assist system in the pedal operation, the magnitudes of the EMG signal during the pedal operation with and without assistance are compared.

A. Experimental Environment

The equipment used in this experiment consists of an ankle power-assist system, a cockpit part, a treading force measuring part, and a display. The height of the cockpit part, the distance from the pedal effort measurement part, and the seat whose seat angle and backrest inclination are adjustable were used. The pedal operation force at the time of depression is measured with an attached strain gauge on an iron plate that imitates an accelerator pedal. The angle of the iron plate is adjustable. In addition, the measured pedal operating force was shown on the display in real time during the experiment. In this experiment, three kinds of seat styles and pedal angles of sedan, SUV and sports type are used to verify whether it is applicable to various driving postures.

B. Pedal Operation in Experiment

At first, the subject is asked to adjust the seat with the ankle power-assist system attached, and take a reasonable driving posture. In this state, bottom dorsiflexion operation is performed about 20 times until the weight value of the fuzzy-neuro modifier is not updated (i.e., until the learning of the fuzzy-neuro modifier is finished). The operated force measured on the iron plate is shown on the display in front of the subject, and stepping operation is performed with the maximum operation force 40 N in the pedal operation as the target value. Then, the same operation is performed without the ankle power-assist system. The EMG signals are measured in each operation. This operation is carried out with each of the three driving postures of sedan, SUV, and sports type.

C. Analysis Method

(1) In the three seat types, select the one with the assist force with or without assistance, normalize the time according to the case where there is no assistance for one pedal operation time from depression to the end of depression.

(2) Integrate the RMS value of the EMG signal in one pedal operation with time. Next, the average value per unit time of the integrated value without assistance of each muscle is displayed as a value with 100%, and increase and decrease of the EMG signal are compared. From the result, confirm whether power assist is being performed.

IV. Experimental Results and Discussion

Figs. 5 and 6 show the experimental results with the sedan seat, and Fig. 7 shows the experimental results with all seat types.

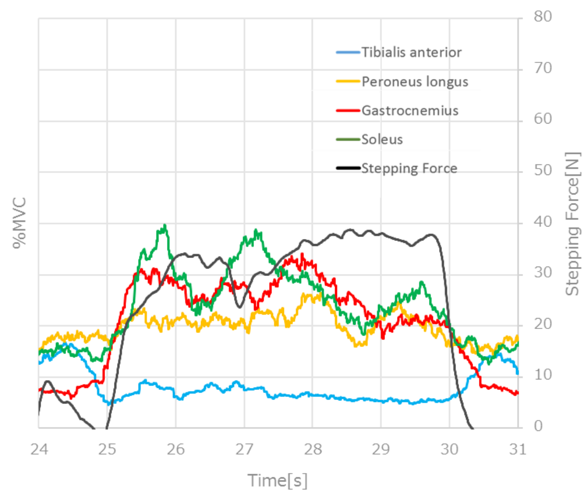

Figure 5. Relationship between stepping force and EMG
Sedan, No-Assist

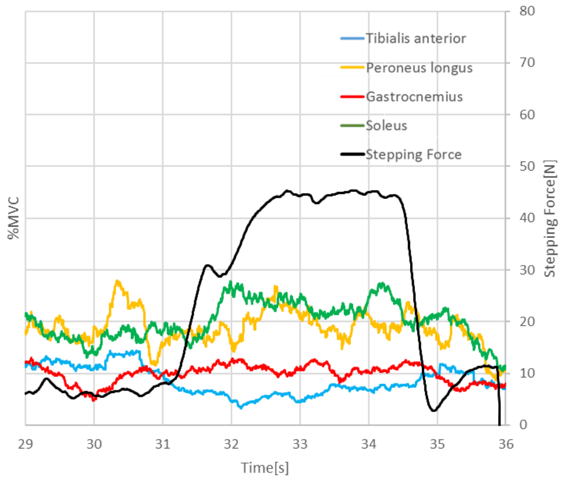

Figure 6. Relationship between stepping force and EMG Sedan, Assist

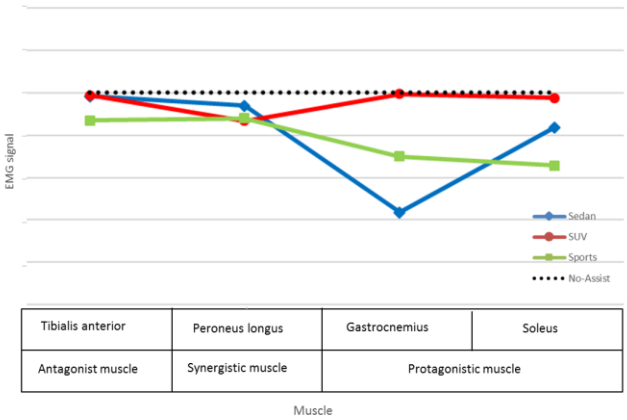

Figure 7. Results of three sheets

In all seat types, reduction of EMG signal of all muscles measured with the assistance was confirmed. For the sedan and sports type seats, the total amount of the measured EMG signals decreased by about 20%, and 1/5 assistance with respect to the driver's ankle torque was confirmed. In the case of the SUV seat type, the reduction rate of the EMG signal is small. In the SUV seat, the angle of the knee is close to a right angle and pedal operation is straight down stepping. As a result, the muscles of the thighs are mainly used for stepping down compare with the cases under the other seat positions, and the effect of bottom flexion of the ankle is reduced, so the reduction rate of the EMG signal is considered to be reduced. Therefore, in the case of the SUV seat, in order to improve the assist, it is necessary to use the muscular strength of the thigh for control. On the other hand, the tibialis anterior muscle, which is the dorsiflexion muscle, is used only for adjusting the stepping force, and the muscular strength is not exerted so much, so the reduction rate decreased.

V. Conclusion

In this paper, the ankle power assist system that assists to generate certain amount of pedal reaction force was proposed. Experimental results showed the effectiveness of this system in pedal operation. Since the proposed system can be applicable to any driver, it will be used to design the acceleration pedal which generates the desired reaction force in accordance with the car acceleration.

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