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Subtle grip force estimation from EMG and muscle stiffness -Relationship between muscle character frequency and grip force-

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***Abstract*—A number of upper limb amputees experience difficulty in picking up a food bowl during a meal, because grip force estimation using EMG currently does not provide sufficient accuracy for this task. In this paper, we propose a grip force estimation system that allows amputees to pick up a bowl with a prosthetic hand by using the properties of muscle stiffness in addition to EMG. We have chosen a tray holding task to evaluate the proposed system. A weight is dropped on the tray and the subjects are expected to control the tray's attitude during the task. Actual grip force, EMG, and muscle stiffness are measured, and the actual measured grip force is compared with the estimated grip force for evaluation. As a result, the proposed algorithm is found to be able to estimate grip force with an error of just 18[N], which is 30% smaller than in the method that uses only EMG. From the result that the response time estimated by proposed system is even less than a human's mechanical reaction time, the effectiveness of the proposed method has been validated.**

I. Introduction

In some Asian cultures, food items including rice and soup are served in small bowls. According to a Japanese prosthetist, a number of upper limb amputees experience difficulty in picking up a food bowl during a meal. The normal custom is to handle a bowl with one hand and a fork or a spoon with the other hand while in front of a table. Controlling a fork or a spoon is much more difficult than simply picking up a bowl. Thus, amputees often use the unaffected side to pick up forks and spoons, which means they are required to use the affected side to handle their food bowl.

The bowl receives multiple forces from different directions during the meal. Especially when we use a bowl containing a liquid such as soup, the bowl's center of gravity (COG) becomes unstable. It requires amputees to apply very subtle controls on the bowl's attitude. At present, grip force estimation using electromyography (EMG) does not provide sufficient accuracy to control a soup-filled bowl because of the low S/N ratio. However, EMG is very useful with fast and large movements because of certain advantages regarding response time.

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II. Purpose

As mentioned, there is the need for developing a prosthetic hand that is capable of grasping and picking up a bowl. Thus the purpose of this research is to propose a noble method of grip force estimation which allows amputees to handle a bowl.

In order to achieve this purpose, high accuracy of grip force estimation is required for the proposed system in the low EMG condition, such as when an amputee is applying subtle controls on the bowl. The purpose of research is to evaluate the proposed system by comparing its response time and estimation error with previous method that uses only EMG.

III. Method

A. *Grip force estimation from multiple measures of muscle activity*

As stated earlier, grip force estimation using EMG does not provide sufficient accuracy to control a soup-filled bowl, though EMG does have a fast response time. The proposed system therefore uses two different measures of muscle activity: it uses muscle stiffness in addition to EMG. There are two reasons why we have selected muscle stiffness. One is that the signal provided by the muscle stiffness sensor is likely to be larger than the EMG signal. We inferred this because muscle stiffness can be easily sensed on touching with the hand. We therefore figured that muscle stiffness could provide a higher S/N ratio than EMG. The other reason is that a change takes place in muscle stiffness on contraction of the muscle. This implies that muscle stiffness may hold information on the extent of muscle contraction. EMG contains information on how much the muscle "will" contract, but not on how much the muscle "has" contracted. Thus, our grip force estimation system consists of EMG for shortening the response time and muscle stiffness for better accuracy of estimation.

B. *Method of measuring muscle stiffness*

The proposed system needs a special sensor for muscle stiffness that can detect muscle stiffness in real time. Most muscle stiffness sensors work by measuring skin displacement when a probe is pushed against the skin. Because this muscle stiffness sensor needs to be constantly pushed against the skin throughout the experiment, we decided to use a different and more comfortable method to measure muscle stiffness.

The newly developed muscle stiffness sensor uses character

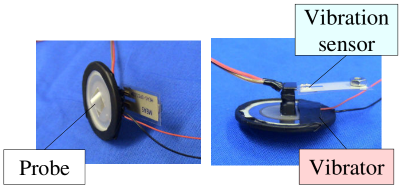


Fig. 1. Developed real-time muscle stiffness sensor using character frequency. It consists of two piezo elements; one is used for sensing vibration, and the other for generating vibration. These piezo elements and amplifier together constitute a simple oscillating system.

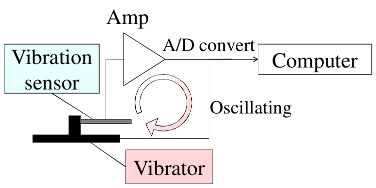


Fig. 2. Block diagram of muscle stiffness sensor's oscillating loop. Oscillating frequency is then calculated by short-time Fourier transform (STFT) from acquired data.

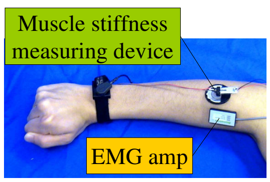


Fig. 3. Muscle stiffness sensor and EMG amp attached position, which is above the long palmar muscle.

frequency to get muscle stiffness, as there is known to be a close relationship between stiffness and character frequency [1]. This type of stiffness sensor does not require a probe to be pushed against the skin; thus, it can measure muscle stiffness continuously and more comfortably for the subjects.

Fig. 1 shows the new muscle stiffness sensor. It consists of two piezo elements; one is used for sensing vibration, and the other for generating vibration. These piezo elements and amplifier together constitute a simple oscillating system (Fig. 2). Oscillating frequency is then calculated by short-time Fourier transform (STFT) from acquired data. This sensor is attached above long palmar muscle through the skin (Fig. 3).

Using this muscle stiffness sensor, the value of muscle stiffness can be observed to change even when the subjects change their posture without muscle contraction. We investigated the relationship between muscle stiffness and change of lower arm posture (Fig. 4) with the developed sensor and plotted it as shown in fig. 5.

C. Estimation algorithm

The proposed system consists of the estimation algorithm and a muscle stiffness sensor. The details of the proposed algorithm are shown in expression (1) and fig. 6. The proposed algorithm combines EMG with muscle stiffness to estimate the grip force. First, the EMG data is filtered with a low pass filter (LPF) for noise reduction. Oscillating frequency veering of muscle stiffness sensor is calculated by taking difference between initial frequency and mean frequency. Finally, the low pass filtered EMG value and temporally-integrated muscle stiffness value are added.

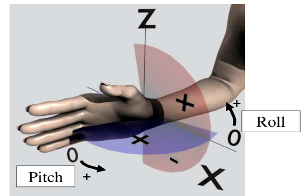


Fig. 4. Without muscle contraction, we investigated the relationship between muscle stiffness and change of lower arm posture in axes above.

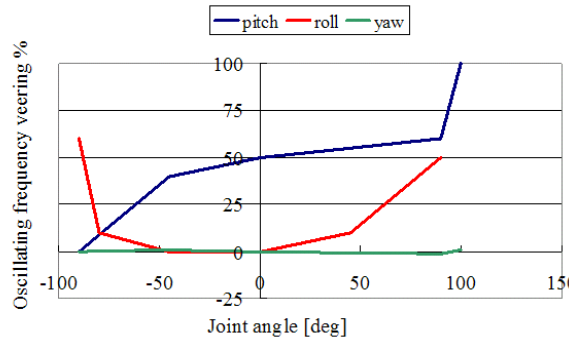


Fig. 5. Muscle stiffness shifting caused by the subject's posture change. In pitch and roll axes, muscle stiffness is drastically changed by posture change, however the voluntary muscle contraction can be detected by observing EMG levels, either.

TABLE I
DESCRIPTION OF VARIABLES IN THE EXPRESSIONS

Symbol	Physical amount
$E(t)$	EMG level
$E_{lp}(t)$	low pass filtered EMG level (cutoff frequency = 1.0[Hz])
$F(t)$	muscle stiffness sensor's mean oscillating frequency
F_{base}	muscle stiffness sensor's initial oscillating frequency
K_1	multiplying factor
K_2	multiplying factor
offset	offset adjustment
$Ef(t)$	estimated value

Multiplying factor, offset adjustment are calculated automatically.

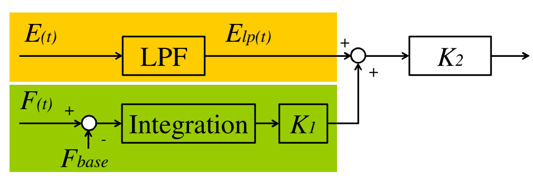


Fig. 6. Block diagram of proposed algorithm which combines EMG with muscle stiffness. First, the EMG data is filtered with a low pass filter (LPF) for noise reduction. Oscillating frequency veering of muscle stiffness sensor is calculated by taking difference between initial frequency and mean frequency. Finally, the low pass filtered EMG value and temporally-integrated muscle stiffness value are added.

$$Ef(t) = K_2 \cdot \left[K_1 \cdot \int \{ F(t) - F_{base} \} + E_{lp}(t) \right] + offset \quad (1)$$

IV. EXPERIMENT

A. Target task and method of evaluation

With due considerations to the need for picking up a bowl, a tray-holding task is chosen for evaluation. Fig. 7 shows the experimental condition. In order to evaluate the proposed system in a low EMG condition, subjects use two different weights during the task. The weight is placed on the tray right after the task has been started. Actual grip force, EMG and muscle stiffness are measured, and actual measured grip force and estimated grip force are compared for evaluation.

B. Experimental-result and data calculation

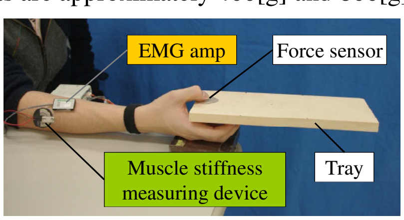
Fig. 8 shows measured grip force (a), low pass filtered EMG (b), and muscle stiffness sensor's mean vibration frequency (c). All data are measured in sampling frequency 5.0[kHz]. The weight is placed on the tray at around 1.4[s], and the grip force is seen to increase. After the grip force has reached a peak, the tray is held still. Mean frequency, fig. 8 (c), is calculated by multiplying highest 5 amplitudes by its frequencies in STFT spectrogram. Fig. 9 shows temporally-integrated mean frequency of muscle stiffness sensor. Compare to fig. 8 (a), Temporally-integrated mean frequency has close relationship with grip force.

RMS error is evaluated within t_0 through t_2. t_0 is the time which is 0.3[s] before the measured grip force reaches its maximum grip force. t_2 is 1.0[s] after t_0. Time delay of estimation is evaluated by comparing t_1. t_1 is the time which the grip force reaches its maximum grip force. Initial oscillating frequency, "F_{base}" in table I, is determined by averaging first 1.0[s] of oscillating frequency. According to fig. 8 (c), muscle stiffness sensor's mean oscillating frequency seems unstable. However, temporally-integrated muscle stiffness sensor's mean oscillating frequency (Fig. 9) is closer to the measured grip force (Fig. 8 (a)).

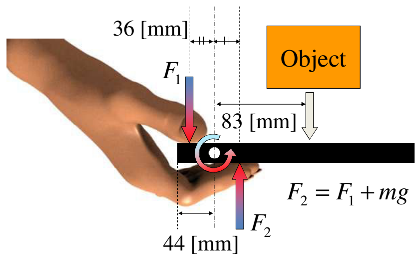
C. Estimation

Fig. 10 is time normalized estimation graph, showing from t_0 through t_2 of averaged all data (n=10). Fig. 10 shows both the measured and the estimated grip force. According to fig. 10, the proposed system is rather more stable than the previous method especially when the bowl is held stably because the estimated value of the proposed system is closer to the actual value than in the previous method.

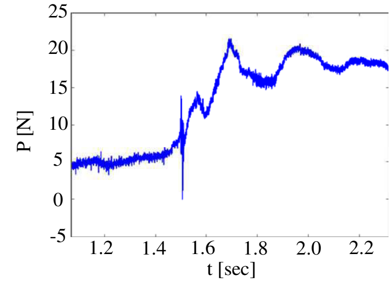
Fig. 11 (a) shows RMS error for each load weight. These two weights are approximately 400[g] and 800[g], equivalent



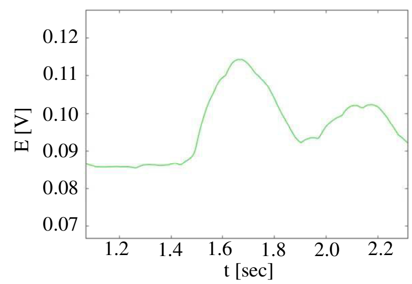
(a) Force sensor, EMG amp and developed muscle stiffness sensor are used. Tray is approximately 150[g].



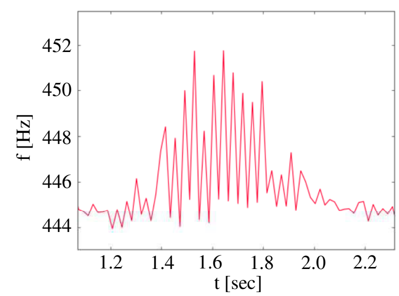
(b) Positional relationship among load weight, hand and tray.
Fig. 7. Experimental condition in tray-holding task.



(a) Measured grip force. The weight is placed on the tray at around 1.4[s].



(b) Low pass filtered EMG



(c) Muscle stiffness sensor's mean oscillating frequency
Fig. 8. Raw data from each sensors. (a) for grip force, (b) for low pass filtered EMG, (c) for muscle stiffness sensor's mean oscillating frequency.

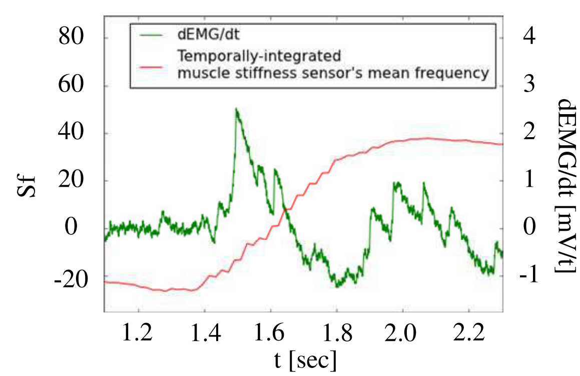


Fig. 9. Temporally-integrated muscle stiffness sensor's mean oscillating frequency and temporally-differentiated EMG.

to a cup of water and a bowl of noodle stew. According to Fig. 11 (a), the proposed estimation system reduced RMS error by 30% from the method that uses only EMG.

V. Evaluation and Discussions

Characteristics of the proposed system such as RMS errors or estimation delay are shown in fig. 11 and table II. The estimation delay of proposed estimation algorithm (34[ms]) is still shorter than a human's mechanical reaction time

(200–300[ms]) [2]. In addition, averaged dispersion of RMS error is smaller in proposed algorithm (Table II). In previous research, frequency to voltage convert (FVC) circuit has been used for acquire oscillating frequency of muscle stiffness sensor [3], in contrast to this paper, STFT. Comparing FVC circuit method with STFT method, RMS error is lower in FVC circuit method, estimation delay is shorter in STFT method. It would appear that the time constant of FVC circuit made estimation delay longer.

In both methods, dispersions for 400[g] load are larger than dispersions for 800[g] (Fig. 11 (b)) because EMG and muscle stiffness value for 400[g] load are small, making estimated grip forces unstable. Fig. 12 shows measured grip force and estimated grip force from only muscle stiffness. Muscle stiffness seems to have a correlate with the amount of grip force, however the detail of grip force have been lost. Thus in the proposed algorithm, it would appear that EMG holds detailed information of grip force, whereas muscle stiffness holds stationary error information of grip force.

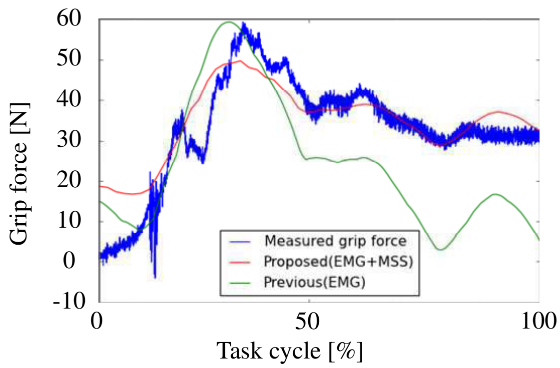
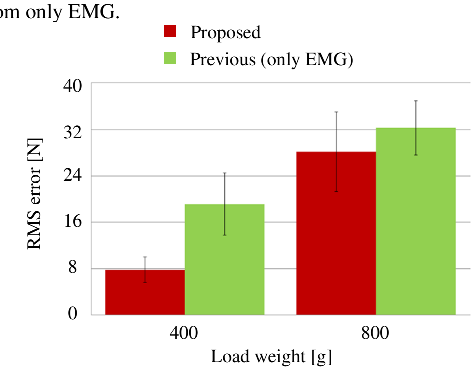
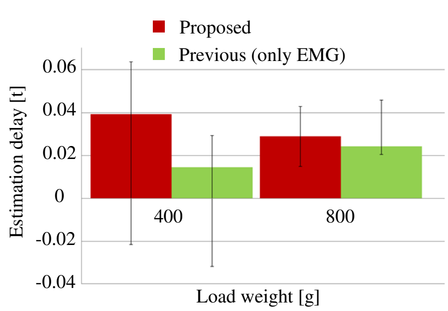


Fig. 10. Estimation result (load weight = 400[g]), showing measured grip force, estimated grip force from EMG and muscle stiffness, estimated grip force from only EMG.



(a) RMS error comparison of proposed method with previous method



(b) Estimation delay comparison of proposed with previous method

Fig. 11. Comparison of proposed method with previous method

TABLE II
CHARACTERISTICS OF ESTIMATION SYSTEM

	Load [g]	RMS error [N]	Estimation delay [ms]
Only EMG	400	19.1±5.4	14.6±36.0
	800	32.3±4.7	24.4±25.2
Proposed method EMG+muscle stiffness	400	7.8±2.2	39.2±43.6
	800	28.2±6.9	29.0±14.0

Estimation delay is calculated by comparing each peak times (t_1) of estimated grip forces with the peak time (t_1) of measured grip force.

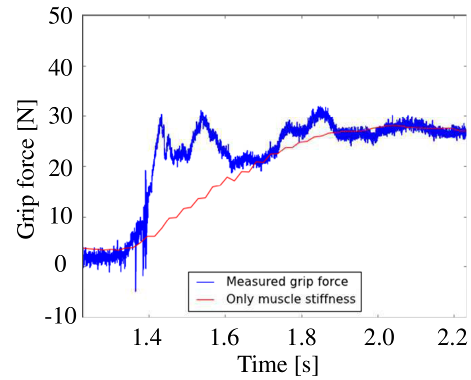


Fig. 12. Comparison between measured grip force and estimated grip force from only muscle stiffness. Muscle stiffness seems to have a correlate with the amount of muscle contraction, however the detail of grip force have been lost.

VI. CONCLUSIONS AND FUTURE WORK

In this research, a novel grip force estimation system which uses both EMG and muscle stiffness is proposed, and a special muscle stiffness sensor which can acquire muscle stiffness in real time and also an algorithm to combine EMG with muscle stiffness to estimate grip force have been developed.

By using muscle stiffness in addition to EMG, the proposed system reduces RMS error by 30% from the error of an estimation method that uses only EMG. Also, the estimation delay is still shorter than a human's mechanical reaction time. This result indicates the possible effectiveness of proposed algorithm.

To validate the effectiveness of the proposed system, further researches have to be done, such as attaching another muscle stiffness sensor and EMG sensor onto antagonist muscle, and estimate grip force with more complicated task.

As future works, we are going to develop a kinesthetic feedback system that allows amputees to control a prosthetic hand easily.

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