2019 IEEE International Conference on Cyborg and Bionic Systems (CBS)
Munich, Germany, September 19-20, 2019

Quantification of Extent of Muscle-skin Shifting by Traversal sEMG Analysis Using High-density sEMG Sensor

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***Abstract*— Surface electromyography(sEMG) measurement has been an essential approach to analyze human behaviors because we can generally consider that sEMG signals represent the muscle activities as the final output of our nerve system. One of the most serious problems for considering sEMG signal as the muscle activity is the shift of the relative position between muscles and skin depending on a posture. The motion of forearm rotation is the prominent example of muscle-skin shifting depending on postural changes. The sEMG signal from a sensor may represent the different muscle activity when the muscle-skin shifting is happened. In this study, we discuss a method to quantify the muscle-skin shift from the sEMG signals in response to the postural changes. We use the high density sEMG sensor that is possible to measure sEMG signal as the potential map. We proposed the computation algorithm to quantify the amount of muscle-skin shifting based on the change of the sEMG signals in response to the postural changes. We conducted the experiments of wrist extension motions under three different forearm postures: forearm pronation, natural posture and forearm supination. Experimental results from three healthy subjects show that we can quantify the extent of muscle-skin shifting as an angle by using proposed algorithm.**

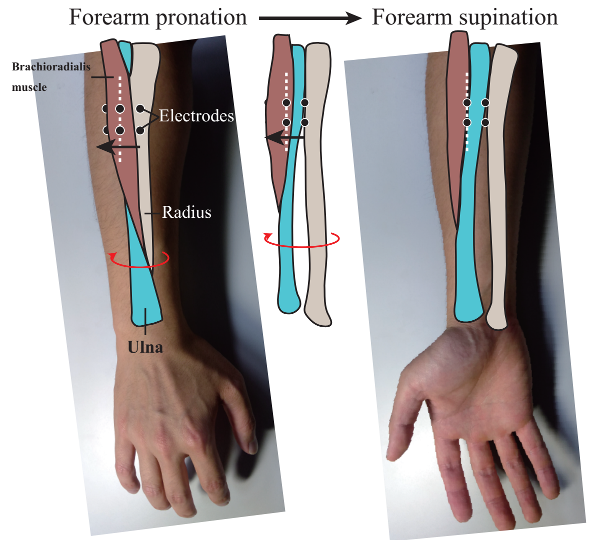

Fig. 1. Muscle-skin shifting in forearm pronation/supination. Electrodes with white dots line are putted on the skin above the brachioradialis muscle in the forearm pronation condition. In the forearm supination motion, the brachioradialis muscle is moved to follow a bone, and the electrodes are also moved because the skin is moved by the muscle shifting. However, since the muscle and the skin are no fixed, the amount of the movement of the muscle and the skin will be difference. As the result, that different causes the muscle-skin shifting.

I. Introduction

Nowadays, surface electromyography(sEMG) measurement has been indispensable in human behavior researches. The sEMG signal measurements are the very useful non-invasive method to estimate the muscle activities. Therefore, the sEMG signal is applied to further understanding of our motion control principle, to wearable device controls such as myoelectric prosthesis, to quantification of rehabilitations and so on.

Recent advancements of muscle synergy analysis are one of the most prominent examples where the sEMG signals are used to analyze and understand the human behaviors. Bernstein [1] argued that human beings had generated their motions by the combination of spatial patterns and temporal patterns of muscles, which are smaller number than the number of muscles. He called it as muscle synergy [2]–[7]. An et al. showed that three muscle synergies had been enough for young subjects to stand up, and four muscle synergies were used for elder subjects to stand up [2], [3]. Ivanenko et al. showed that human beings had been able to walk by five muscle synergies [4]. Muscle synergy is used as an evaluation index of a rehabilitation intervention for post-stroke patients [5]–[7]. The sEMG signals have been used for not only the motion analysis but also high-affinity control of a myoelectric prosthesis arm.

The myoelectric prosthesis arm can control a grasping motion based on the sEMG signals measured from users' forearm [8]. It is considered that users easily obtain a grasping function to grasp the object by using the sEMG signals reflecting the human motion intention. In addition to that, by combining the sEMG signals and machine learning methods, the myoelectric prosthesis arm with five fingers have been developed to realize more complex motions like human beings [9]–[11].

These analyses and controls are conducted based on the sEMG signals. In other words. The success of the analysis and the control strongly depends upon the waveform of the sEMG signals. A serious issue for considering the sEMG signal as the representation of muscle activity is the relative position shifting of muscle and skin depending on

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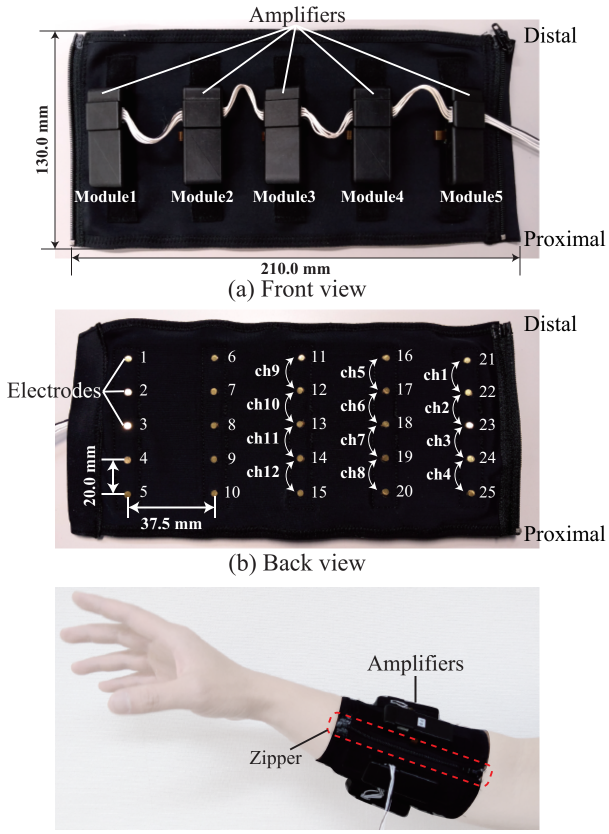


(a) Front view

(b) Back view

(c) View in wearing on forearm

Fig. 2. High-density sEMG sensor: (a) Front view. (b) Back view. (c) View in wearing on forearm. The detail is shown in Section II B.

postures(see Fig. 1). It is empirically known that the muscle and the skin are relatively shifted depend on a posture such as a forearm supination. It suggests that even though putting the electrodes on specific point of the skin, the relative position of the muscle and the electrodes will be shifted depending on the posture.

This phenomenon will affect the waveform of the sEMG signal because some muscles approach the sensor and get away from the sensor with the postural changes. Therefore, the change of the waveform in response to the postural changes may lead miss-controlling and a wrong analysis. In addition to that, some researches clam about the effect of the electrode position on a motion classification using the sEMG signals [12]–[14]. Even in the field of functional anatomy, the quantification of the amount of muscle-skin shifting is under discussions.

In order to solve the issue, it is necessary to quantify the muscle-skin shifting. In this paper, we will discuss the method to quantify the muscle-skin shifting from sEMG signals with focusing on the forearm rotation. We use a high-density sEMG sensors to quantify the muscle-skin shifting, which is possible to measure the change of the sEMG signals as the flow of the potential map.

The rest of this paper is organized as follows: In Section II, the details of our high-density sEMG sensor are explained. In Section III, wrist extension experiments with different postures are conducted, and it is shown that the postural change affects the waveform of the sEMG signals, and the change of the muscle activity among the different postures can represent the muscle-skin shifting. In Section IV, it is proposed that the computational algorithm to quantify the muscle-skin shifting from the sEMG signals. In Section V, we will conclude the results in this paper.

II. High-density sEMG sensor

A. Problems with conventional high-density sEMG sensors

Many high-density sEMG sensors have been proposed to measure and analyze the sEMG signals in detail [16]–[18]. Marco et al. studied about muscle fatigue by evaluating a propagation speed of the potential difference on electrodes [16]. Zhu et al. proposed an evaluation method for swallowing by a potential map of the muscle activities using the high-density sEMG sensor [17]. An advantage of these sensors is that the change of the muscle activity can be visualized as a two-dimensional flow. However, these sensors easily suffer from motion noise because the electrodes and amplifiers are located far, so these sensors are usually applied to isometric motor tasks.

The most important things of the high-density sEMG sensor are to stably measure the sEMG signals and to easily use. Also, in case that the sEMG signals are not synchronized, making it difficult to detail analyze the human behavior. In addition to that, time consuming of installation and gel disturb the use of the sensors.

Based on these problems, our high-density sEMG sensor is developed with the following features:

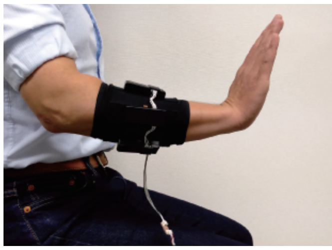
1) The electrodes and the amplifiers are located close in order to amplify measured signals immediately.
2) All sEMG signals are synchronized by the serial communication.
3) The subject can use the sensor like just wearing a T-shirt without gel.

B. Configuration of proposed sensor

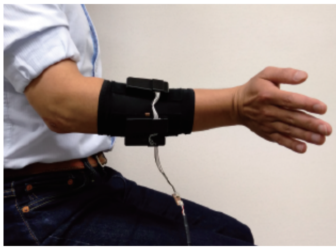
Figure 2 shows the proposed sensor solving issues that conventional high-density sEMG sensors have. This sensor is designed to measure the sEMG signals from the forearm. Electrodes and amplifiers are fixed to the cloth. A zipper is equipped with a stretchable cloth for subjects to easily wear this sensor.

Figure 2(a) shows that the vertical width of this sensor is 130.0 [mm], and the horizontal width is 210.0 [mm]. It is considered to be enough size for subjects to wear it on subjects' forearm. There are five modules(Module 1-5) that have amplifiers, and each module is connected by cables for the serial communication. The electrodes are placed behind the amplifiers in order to amplify measured signals immediately.

The proposed sensor has totally 25 dry electrodes(see Fig. 2(b)). The number of electrodes is enough to say that it is the high-density sEMG sensor [15]. Subjects can



(a) Wrist extension with forearm pronation



(b) Wrist extension with natural posture

(c) Wrist extension with forearm supination

Fig. 3. Position of proposed sensor and motions in experiment: (a) Wrist extension with forearm pronation. (b) Wrist extension with natural posture. (c) Wrist extension with forearm supination. The subject wears the proposed sensor around the middle of his/her right forearm so that Module 3 is on the line connecting an elbow and an ulna at (a). The subject sits on a chair and bend an elbow about 90.0 [deg] in the experiment.

comfortably use the proposed sensor without the gel thanks to the dry electrodes. One column has five electrodes at 20.0 [mm] intervals. Each row is arranged at 37.5 [mm] intervals. The voltage between the electrodes in the column is measured, that is, four sEMG signals can be measured in one column. We can totally measure 20 sEMG signals(Five modules$\times$Four channels in one column) by this sensor.

Figure 2(c) is an overview when the subject wears the proposed sensor on his forearm. You can see that the proposed sensor can be placed the middle of the forearm and attached on the forearm properly thanks to the stretchable cloth and the zipper. In assuming that the forearm is a cylinder, each module is placed on the forearm at 72.0 [deg] intervals.

The sEMG signals are measured with a sample frequency of 2.0 [MHz]. The measured signals are converted by an analog-to-digital converter from 0.0 [V] to 3.3 [V]. Its resolution is 16 bits. The converted signals are sent to a PC through USB connection.

III. sEMG Measurement Experiment of Wrist Extension Motion with Different Postures

The sEMG measurement experiments are conducted by using the proposed sensor. In this experiment, we target wrist extension motions with three different postures: forearm pronation(-90.0 [deg]), natural posture(0.0 [deg]), forearm supination(90.0 [deg]). The purpose of this experiment is to verify the effect of the postures, that is, the muscle-skin shifting on the sEMG signals.

A. Experiment setting

Figure 3 shows the position of the proposed sensor and motions with different postures in the experiment. The subject wears the proposed sensor around the middle of his/her right forearm so that Module 3 is on the line connecting an elbow and an ulna in case of the forearm pronation. We confirm that the subject does not get any pain from the proposed sensor. The subject sits on a chair and relaxes his/her posture before performing.

One trial of the experiment is conducted as follows:

1) The subject naturally bends the right elbow about 90.0 [deg].
2) The subject extends his/her wrist about 90.0 [deg] and returns to an original position in 1.0 [Hz].
3) The subject repeats a motion of 2) five times.

We ask the subject to conduct above trial under different three postures: forearm pronation(-90.0 [deg]), natural posture(0.0 [deg]), forearm supination(90.0 [deg]). We assume that the muscle-skin shifting is occurred at the changing of postures and can see the effect of the muscle-skin shifting on the sEMG signals.

Three healthy subjects aged 31$\pm$8 participate in this experiment. We explain the purpose and the process of this experiment to the subjects, and the subjects understand it and agree to participate in this experiment.

B. Experiment result

Figure 4 is the time series of 20 sEMG signals after signal processing that is to set a mean value of raw sEMG signals to zero, to calculate absolute values, and to low-pass filter with a cutoff of 1.0 [Hz]. A red part of Fig. 4 represents a forearm pronation condition, a green part represents a natural condition, and orange part represents a forearm supination condition. There are five peaks in each condition, representing five wrist extension motions. You can see that the amplitude, especially, in ch5 decreases, on the other hand, the amplitude in ch13 increases. In this experiment, the subjects extend the wrist about 90.0 [deg] in each posture. This figure can show that the postural change affects the waveform of the sEMG signal because some muscles approach the sensor, and some muscles get away from the sensor by postural changes.

Figure 5 shows potential maps calculated from 20 sEMG signals in different postures. There is a peak in each map, which represents the position where muscles strongly activate. You can see that the peak is shifted along the direction from Module 1 to Module 5. When the posture is changed from the forearm pronation to the forearm supination, the forearm is rotated from Module 1 to Module 5. The coincidence between a shift direction of the peak and a rotation direction of the forearm suggests that it is possible to

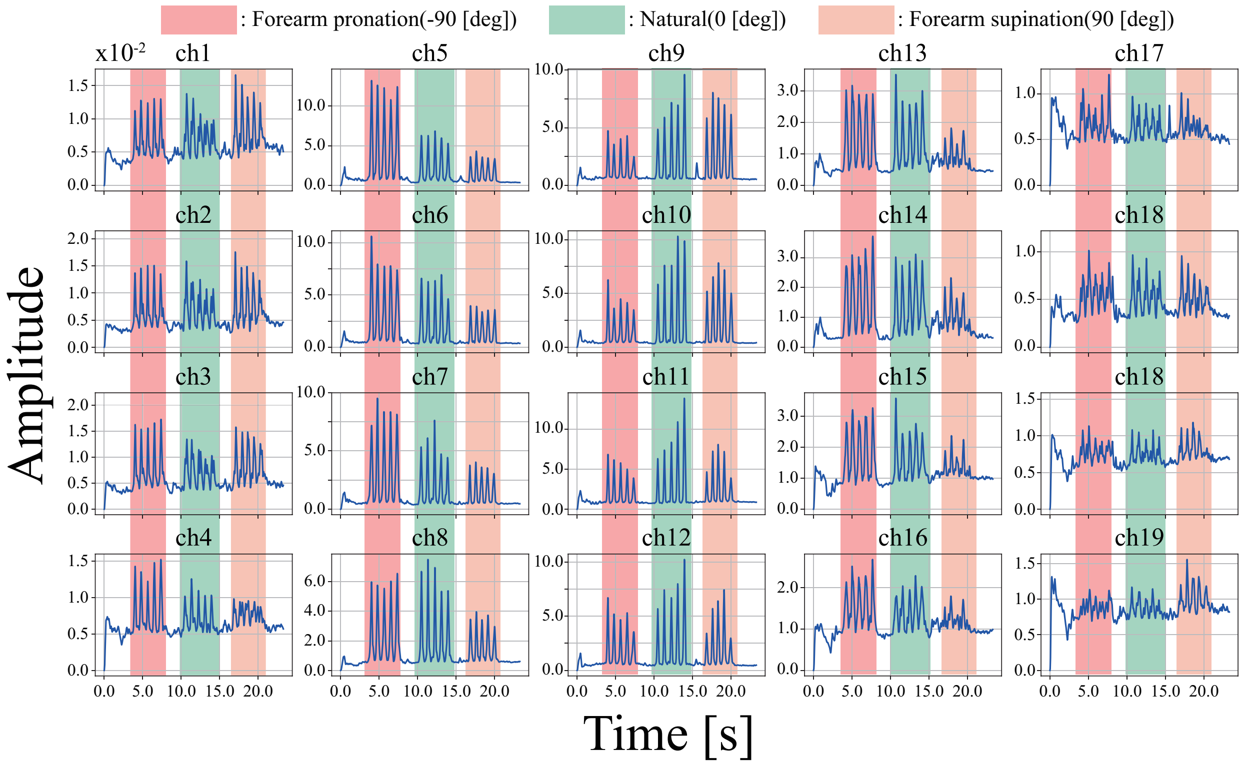


Fig. 4. Time series of 20 sEMG signals in experiment. The signals are after signal processing that is to set a mean value of raw sEMG signals to zero, to calculate absolute values, and to low-pass filter with a cutoff of 1.0 [Hz]. Red parts are under a condition of the forearm pronation, green parts are under a condition of the natural, and orange parts are under a condition of the forearm supination. There are five peaks in each condition. This figure shows that the amplitude of the signal in ch5 decreases, on the other hand, the amplitude of the signal in ch13 increases after changing the posture. It suggests that the postural changing, that is, the muscle-skin shifting affects the waveform of the sEMG signals.

quantify the muscle-skin shifting based on the change of sEMG signals among the postures.

IV. Traversal sEMG analysis quantifying muscle-skin shifting

Next, we develop an analysis method to quantify the muscle-skin shifting based on the change of sEMG signals among the postures. In this study, we focus on the effect of the forearm pronation/supination, so we quantify the muscle-skin shifting as a rotational angle. In this analysis, we use the sEMG signals not in the column but in one row in Fig. 4. We call this analysis as traversal sEMG analysis.

We make vectors from the sEMG signals of one row of Fig. 4 at a specific moment t [s], which the length of each vector is the amplitude of each sEMG signal. The vectors are placed in x-y coordination to overlap the place of modules of the sensor when the subjects wear the sensor. The modules of the proposed sensor are placed at 72.0 [deg] intervals in assuming that the forearm is a cylinder, so the vectors made by the sEMG signals are arranged at 72.0 [deg] intervals. Figure 6 is an overview of an above method when the vector made by the sEMG signal in ch1 is 0.0 [deg]. This is nothing but representing the muscle activity on the coordinates fixed on the skin. The solid line vectors are the vectors made by the sEMG signals.

When each point in Fig. 6 is supplemented with a spline curve, n vectors can be created. The dots line vectors in Fig. 6 are the vectors after supplementing with a spline curve. A total vector at the specific moment t [s] can be calculated as

$$\begin{bmatrix} x(t) \\ y(t) \end{bmatrix} = \sum_{i=0}^{n} \begin{bmatrix} a_i(t)\cos\left(\frac{2\pi i}{n+1}\right) \\ a_i(t)\sin\left(\frac{2\pi i}{n+1}\right) \end{bmatrix}, \tag{1}$$

where i of $a_i(t)$ is a subscript, $a_i(t)$ is a vector length, and $n+1$ is the number of vectors obtained after supplementing. A red vector in Fig. 6 represents the total vector. This total vector points in the direction of the sensor that measures strong muscle activity. In other words, the total vector can represent the bias of the muscle activity during the motion.

From Eq. 1, the angle of the total vector is calculated as follow:

$$\theta(t) = \tan^{-1}\left(\frac{y(t)}{x(t)}\right). \tag{2}$$

As a hypothesis, when a periodic motion is conducted, the muscles activate periodically. For example, we bend and stretch our elbow, a biceps brachii activates, then a triceps brachii activates periodically. It suggests that the bias of the muscle activity, that is, the total vector and its angle are also changed periodically. If the muscle is shifted by the postural change, and the muscles activate periodically after the postural change, a mean value of the angle is also shifted in response to the postures. Therefore, the change of

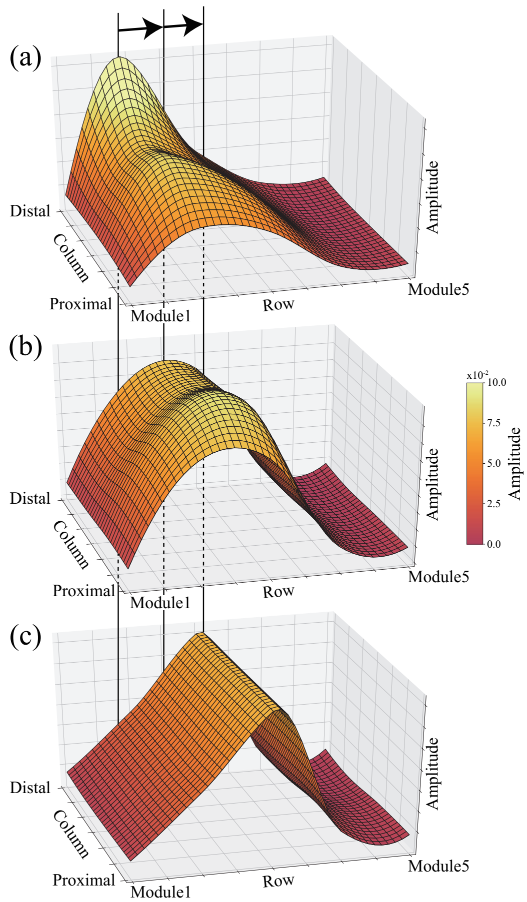


Fig. 5. Potential maps: (a) Calculated from 20 sEMG signals at 5.7 [s]. This moment is at the wrist extension with the forearm pronation(-90.0 [deg]). (b) Calculated from 20 sEMG signals at 12.2 [s]. This moment is at the wrist extension with the natural posture(0.0 [deg]). (c) Calculated from 20 sEMG signals at 19.0 [s]. This moment is at the wrist extension with the forearm supination(90.0 [deg]). There is a peak in each map. The peak means a position where the sensor measures strong muscle activity. The peak shifting suggests that it is possible to quantify the muscle-skin shifting based on the change of sEMG signals among the postures.

the mean value of the angle can quantify the muscle-skin shifting.

$\theta(t)$ is calculated in each posture by using the sEMG signals in second row of Fig. 4, and $n = 359$. Figure 7(a) shows the time series of $\theta(t)$ in the wrist extension with each posture. You can see that, as the hypothesis, $\theta(t)$ changes periodically in periodic wrist extension motions. Figure 7(b) shows mean values and standard deviations of Fig. 7(a). These are calculated from five wrist extension motions in each posture. You can see that, as the hypothesis, a mean value of $\theta(t)$ is shifted in response to the postural change. Figure 7(c) shows the mean value of $\theta(t)$ of each subject after the normalization. You can see that there is same tendency in each subject that $\theta(t)$ increases as the forearm is rotated. As the result, it can be shown that the bias of the muscle activity can quantify the muscle-skin shifting as the angle.

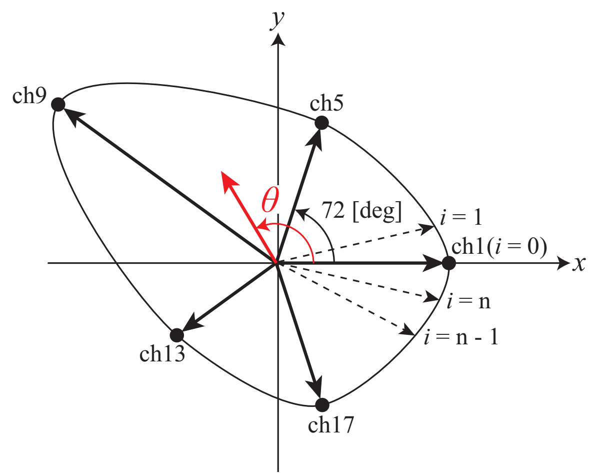


Fig. 6. Overview of traversal sEMG analysis method to quantify muscle-skin shifting. Please see the detail in Section IV.

V. Conclusion

The muscle-skin shifting is the serial issue of the sEMG analysis from the aspect of changing the sEMG waveform in response to the postural change. Quantification of the muscle-skin shifting using the sEMG signals is a key factor to analyze the muscle activities in detail. In this study, we proposed the sEMG analysis method to quantify the muscle-skin shifting by using the sEMG signals and showed, through the experiment, that the proposed method could quantify the muscle-skin shifting as the angle in the wrist extension motion with three different postures.

The high-density sEMG sensor was developed to quantify the muscle-skin shifting by the change of muscle activities across the forearm. There are three important features of the proposed sensor. First, the proposed sensor equips the serial communication to synchronously measure sEMG signals. Second, the proposed sensor has the dry electrodes, the stretchable cloth, and the zipper, so the subject can easily wear the proposed sensor. Third, the electrodes are placed behind the amplifiers in order to amplify measured sEMG signals immediately to decrease the motion noise.

The sEMG measurement experiment was conducted, which was that the subjects extended the wrist under the condition of three different postures: forearm pronation(-90.0 [deg]), natural posture(0.0 [deg]), forearm supination(90.0 [deg]). The experiment results showed that the amplitude of some sEMG signals decreased and increased in response to the postural change even if the subject moved the wrist in the same way in each posture. It suggested that the muscle-skin shifting by the postural change affected the waveform of the sEMG signals.

The traversal sEMG analysis was proposed to quantify the muscle-skin shifting. The essence of this analysis is to represent the muscle activity on the coordinates fixed on the skin. This analysis can comprehensively represent the muscle activity of the forearm as the movement of the vector. We hypothesized that the vector moved periodically in the

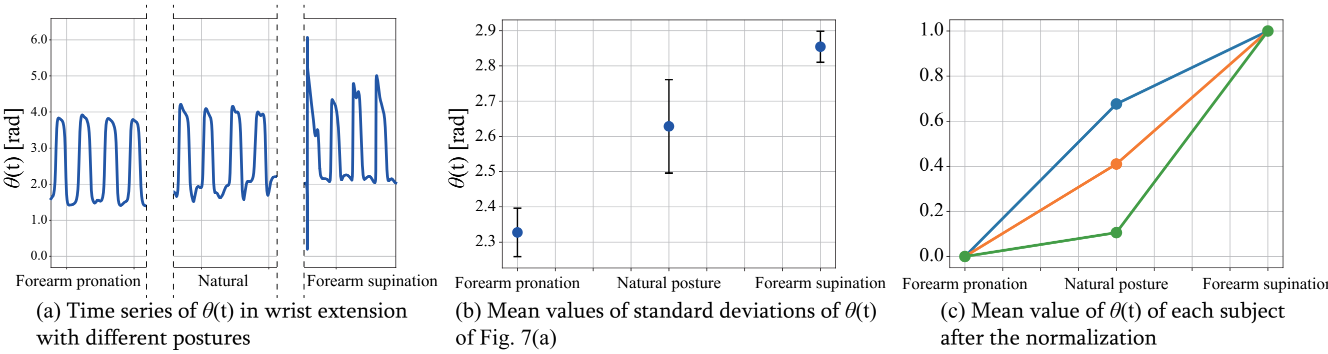


Fig. 7. (a) Time series of $\theta(t)$ in wrist extension with different postures. As the hypothesis, $\theta(t)$ changes periodically in the wrist extension. (b) Mean values and standard deviations of $\theta(t)$ of Fig. 7(a). These are calculated from five wrist extension motions in each posture. As the hypothesis, a mean value of $\theta(t)$ is shifted in response to the postural change, suggesting that the mean value of $\theta(t)$ can represents the muscle-skin shifting. (c) Mean value of $\theta(t)$ of each subject after the normalization. It is calculated by setting a mean value of $\theta(t)$ in the forearm pronation to zero, then normalizing the mean values of each trial in each subject. It shows that there is a tendency in each subject that $\theta(t)$ increases as same direction as the forearm supination.

periodic motion, and the periodic motion of the vector would be shifted by the muscle-skin shifting. This analysis showed that the angle of the vector periodically changed in the periodic wrist extension motions even if the postures were changed. In addition to that, as the hypothesis, the mean value of the angle increased as the forearm was rotated. Therefore, it was shown the mean value of the angle could quantify the muscle-skin shifting.

The results here can be considered as a first step of understanding the muscle-skin shifting and its effect on the sEMG. In order to understand the muscle-skin shifting deeply, we need to anatomically confirm how much shifting is occurred by using CT or an ultrasonic inspection device. Then, we should verify the validity of the proposed analysis with comparing results from the anatomical study and the sEMG study.

As future works of proposed analysis itself, further discussions are required, such as how much resolution of the quantification of shifting the analysis achieves,s and what kind of motions the analysis can be applied. In addition to that, we currently attempt to analyze the muscle-skin shifting after normalizing the sEMG signals using maximal voluntary contraction to verify the difference of the shifting between the subjects properly.

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