31st Annual International Conference of the IEEE EMBS
Minneapolis, Minnesota, USA, September 2-6, 2009

Novel muscle activation sensors for estimating of upper limb motion intention

Hyonyoung Han, and Jung Kim, *Member, IEEE*

***Abstract*— Measurement of muscle activation is important to understand body motion and the exertion of force. This paper presents two novel muscle activation sensors, a piezo cable muscle activation sensor (pMAS) and an optical muscle activation sensor (oMAS). The pMAS measures variations of a flexible piezo cable band that originate from diameter changes of muscle bundles. The sensors are easily attached and can be worn on clothes. The oMAS, which measures the optical density of muscle fibers, has advantages of small size, ease of use, and non-referenced individual sensing. Muscle activations of the upper limb during movements were collected to evaluate the performance of the proposed pMAS, and oMAS, respectively. Furthermore, the relation between movements and sensor signals was analyzed to estimate the upper limb movements.**

I. Introduction

ESTIMATION of motion intention presents a challenge when there is a requirement of fast and adequate response in human-machine interaction (HMI), such as in the cases of exoskeletons, human assisting manipulators, and prosthetic devices, which support movements and supply forces to the user through recognition of the user's motion. To understand body motion and the exertion of force, muscle activity level is an important human physiological parameter. Accordingly, researchers have investigated methods to measure this parameter, which in turn could allow them to evaluate the intentions of the user of HMI device. From the exited signal to the resulting movement, the parameter can be measured via various methods using a muscle activation sensor (MAS). Electromyography (EMG) is a widely employed approach to sense muscle activation, and researchers have proposed various estimation methods of motion intention using EMG, for computer interfaces [1], prostheses [2], and exoskeletons [3]. EMG has advantages over even the fastest activation sensor because the neural signal is measured directly [4]. However, it is susceptible to electromagnetic noises and artifacts. Furthermore, with EMG it is difficult to measure low level and slow activations and long term usage poses problems due to character changes of the signal. Also, EMG requires high sampling frequency and another reference signal on another site is needed. Also, the EMG sensors must be attached directly on the skin, which can cause inconvenience or discomfort to the subject.

To overcome these problems, other measurement methods have been proposed. Mechanomyography (MMG), where the transverse displacement of the skin over a contracting muscle is measured, has been studied for prostheses using an accelerometer [5], a muscle stiffness sensor (MSS) for an assistance device [6], muscle fiber expansion (MFE) sensors for an assisting robot [7], NIR spectroscopy for a prosthetic device [8], and a flexible piezo electric thin film sensor for a human interface [9]. However, other problems remain. In this study, we propose two novel muscle activation sensors for estimating motion intention: a piezo cable muscle activation sensor (pMAS) and an optical muscle activation sensor (oMAS). The pMAS can detect activity level on clothes and can be used easily. The oMAS is small and affordable, operates at low sampling frequency, does not require a reference signal, and is not sensitive to measurement site.

This paper is organized as follows: In Section II, the process of physiological and physical changes in muscle tissue is explained for understanding the muscle activation process. Also, the principles of the pMAS and the oMAS and the signal processing method are introduced. In Section III, the experimental setup and protocols for the tests are outlined. Test performed to evaluate the performance of the sensors are detailed in Section IV. Finally, Section V summaries and concludes this study.

II. Materials

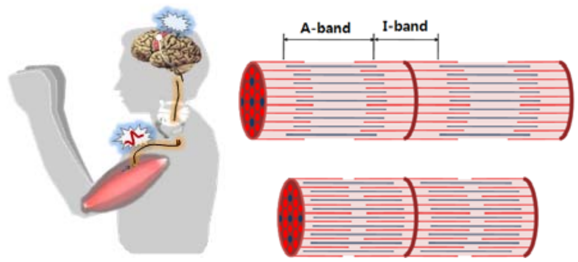
A. Muscle activation

Muscle activation induces human body motions. The limb motions start from the cortex of the brain with a neuro-electrical signal. The signal travels along the spinal cord to individual neurons, a process that can be monitored via electroneurography (ENG), shown in Fig.1.(a). The signal then reaches a motor unit and activates the muscle fiber, and the related activated signal is measured via electromyography (EMG). EMG activates the muscle and contracts the muscle tendons that are related to the motions.

When muscle is activated, the physical properties of the muscle are changed. Muscle fiber is a bundle of myofibrils, which consist of myosin-containing filaments and actin-containing filaments [10]. Fig.1.(b) shows myofibrils in a resting condition and activated condition. When muscle is activated, the myosin filaments contract both sides of the actin filament, and a large portion of each filament is thereby piled up . The length of the A-band region of the myosin

Manuscript received April 23, 2009. (Write the date on which you submitted your paper for review.) This work supported by National Agenda Program of the Korea Institute of Science and Technology (KIST).

J. Kim, H. Han are with the Department of Mechanical Engineering, Korea Advanced Institute of Science and Technology (KAIST), Daejeon, 305-701, Korea (phone: +82-42-350-3231; fax: +82-42-350-5230; e-mail: jungkim@kaist.ac.kr).



(a) (b)

Fig. 1. Muscle activation process; (a) Neural signal path and muscle activation, (b) Muscle fiber contraction process during muscle activation; activated condition (below) and resting condition (above)

filament is fixed at all conditions, whereas the length of the I-band region of the actin filament only is shortened in the activated condition. Therefore, not only muscle fiber but also the muscle becomes shorter, denser, and thicker. The muscle thus becomes stiffer and denser . Also, the cross-section of the muscle fiber is enlarged due to shortening and overlapping of each filament, which leads to expansion of the circumference of the muscle bundle and each limb.

Through these processes, motion of the body and related limbs is achieved. During this process, some neural signals can be obtained, and some physically changed parameters can be detected. In this study, we measure the circumference of the muscle using the pMAS and the density of the muscle using the oMAS, among the various parameters.

B. Piezo cable muscle activation sensor (pMAS)

The piezo cable sensor measures the muscle activity level by detecting muscle volume changes. The flexible piezo cable (Xire, Piezolab, KR) is comprised of piezoelectric materials, which generate an electrical potential in response to applied mechanical stress. Generally, this material is a ceramic-like, hard material, but the material of the cable is flexible enough that it can be bent unrestrictedly. Therefore, the cable generates voltage when its shape is transformed or pressed due to external forces. Using this principle, we developed a muscle activation sensor to detect the change of muscle circumference. Fig.2. shows the shape of the pMAS. The sensor consists of elastic components and the cable. The elastic components support the shape of the sensor and make it possible to change the circumference. To obtain high resolution, the cable should be substantially transformed. Hence, the cable is twisted and turned several times in the band to increase the degree of change of the sensor shape in consideration of spacing between the peak and thickness of the cable.

In normal conditions, the sensor maintains the initial circumference, but after muscle activation, the circumference of the sensor is expanded according to the expansion of the muscle. On the basis of this principle, the pMAS can measure the muscle activation.

C. Optical muscle activation sensor (oMAS)

Optical elements, LEDs, and photo sensors measure muscle activation by sensing the optical density of the

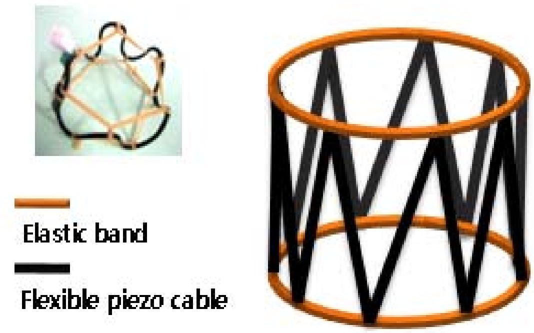


Fig. 2. The shape of the pMAS. The pMAS consists of an elastic band at each side and a flexible piezo cable between the elastic components

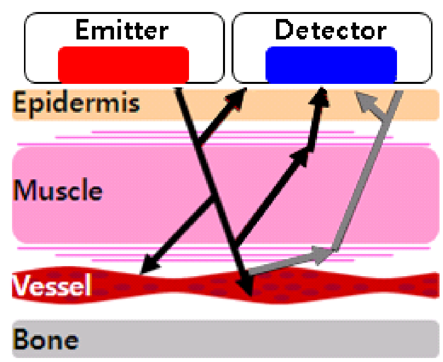
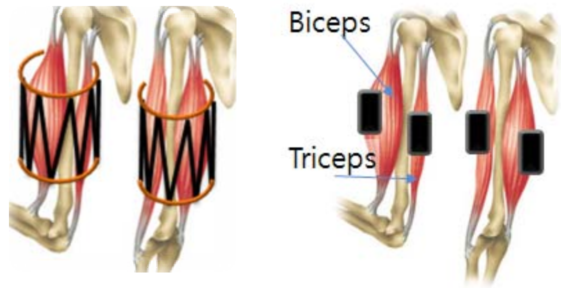


Fig. 3. Principle of the oMAS. The photo sensor detect reflected right on the muscle

muscle bundle. The principle of the sensor is similar to photoplethysmography (PPG) [11], which measures pulse, and NIR spectroscopy [12], which muscle oxygenation and perfusion, but the object of interest in the case of motion frequency is very low frequency, including DC and uses only one light source. When light is directed on to skin tissue, some portion of light is absorbed while some it transmitted or reflected on each tissue, that is, the dermis, muscle, vessel, and bone, as shown in Fig.3. The path of the light is represented as arrows in the figure. The black arrows are muscle related light, and the amount of light is affected by the thickness and density of the muscle. The photo sensor then gathers the reflected light at the muscle. Because muscle is a static component during resting, we can expect that the related information will be DC or a very low frequency component in the output signal. The output value and the reflection rate of the muscle are changed according to the density of the muscle. Section II-A noted that activation causes the muscle to become due to muscle contraction, and the activated dense muscle has a higher value due to increased reflection.

III. Experimental Protocol

The proposed sensors, pMAS and oMAS, measure the muscle activation during upper limb motions and the results are used to evaluate the performance of the sensors. The test measured the muscle activations according to elbow joint motion using each sensor, respectively. Among the elbow



(a) (b)

Fig. 4. Experimental setup (a) pMAS experiment. The circumference of the sensor and the muscle is expanded when the muscle is contracted (b) oMAS experiment. Two sensors are attached on the target muscles, the biceps and triceps.

motion related muscles, biceps brachii and triceps brachii were selected as target muscles. A group of three healthy subjects aged between 20 and 30 years old were tested. The protocols consisted of six elbow angles (0°, 30°, 60°, 90°, 120° and 150°). The protocols for the sensors were as follows: the elbow was held for approximately five seconds at each angle, followed by a rest period of five seconds between each movement. This sequence was repeated three times. All sensors were tested with EMG for comparison. All of the sensor signals were acquired using a data acquisition system (MP35, Biopac, USA) and the data were processed and analyzed by a commercial engineering calculation software package (Matlab, Mathworks, USA).

For detection of limb movements by the pMAS, the sensor was worn on the upper arm where it could cover both muscles, as seen in Fig.4.(a). The oMAS measures the muscle activation by measuring the signal of both muscles, as shown in Fig.4.(b). The performances of each sensor are evaluated by determining the sensor output according to elbow motions. The results were analyzed by comparing both raw data and integrated data to find meaningful physical values.

IV. Experimental Results

A. *Elbow motion estimation using pMAS*

The pMAS measures the muscle activation during the elbow movement. Figure 5 shows the integrated EMG signal and signal processed sensor signal during the movements. The black line depicts the EMG signal and the dashed line is the pMAS sensor signal. Each angle of motions is shown as text above the time axis. Table I shows the results of elbow motion estimation with pMAS, based on the average value of the signal.

When the angle is higher, the EMG signal and the pMAS signal are also increased, almost to the level of linear relation. The value increases and can be presented as a linear equation (1). $\boldsymbol{\theta}$ is the estimated angle of the elbow and $\boldsymbol{x}$ is the pMAS signal. The linear coefficient, $\boldsymbol{a}$, in this case is 0.034 and the offset coefficient, $\boldsymbol{b}$, is 0.296. Through the relation equations, we can estimate the elbow movement from the pMAS signal.

$$\theta = ax + b. \tag{1}$$

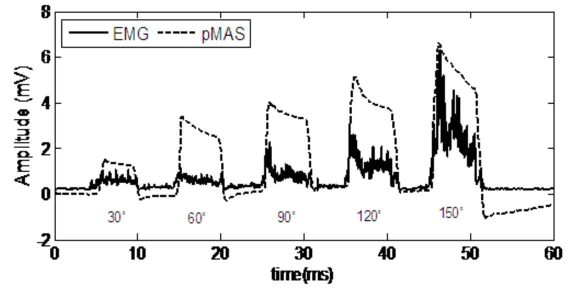


Fig.5. Experimental result of the pMAS test; Raw output signal

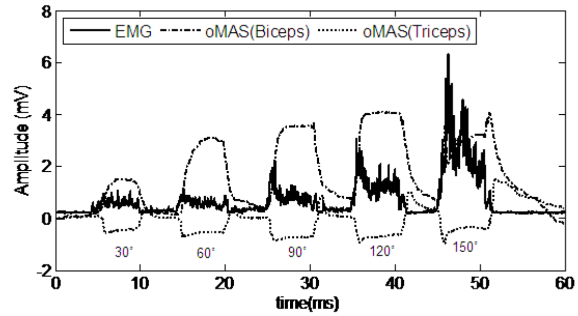


Fig.6. Experimental result of the elbow movement using oMAS.

B. *Elbow motion estimation using oMAS*

The oMAS measured the activation of the elbow motion related muscles, i.e., the biceps and triceps. A plot of the experimental results is presented with the EMG signal in

TABLE I
RESULT OF ELBOW MOTION ESTIMATION WITH PMAS

Angle (°)	Average value (mV)
0	0.00
30	1.337±0.065
60	2.848±0.259
90	3.541±0.206
120	4.074±0.367
150	5.431±0.556

TABLE II
RESULT OF THE ELBOW MOTION ESTIMATION WITH OMAS

Angle (°)	Maximum value (mV)	
	Biceps	Triceps
0	0.0	0.0
30	1.405±0.125	-0.442±0.053
60	2.980±0.127	-0.549±0.037
90	3.508±0.068	-0.745±0.028
120	4.070±0.025	-0.701±0.039
150	3.042±0.118	-0.351±0.042

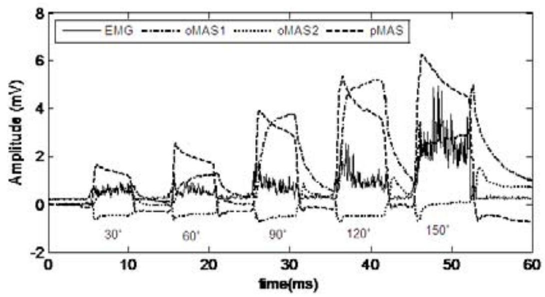


Fig.7. The raw output signal of pMAS and oMAS signal during the elbow movement

Fig.6. The black line is the EMG signal, the dash-dotted line is the signal from the biceps and the dotted line is from the triceps and the text above describes the motion angles. Similarly with EMG, oMAS signals show some patterns. During the movement, the bicep signal increases but the tricep signal decreases, because each muscle has a different behavior; the bicep is contracted and becomes denser, whereas the triceps relaxes.

Table II shows the linear relation between the average value of the signal and the elbow angle. The bicep signal and angle shows a linear relation except at 150.° The bicep signal has a linear relation, where ***a*** is 0.034 and ***b*** is 0.343. The tricep case shows small variation and a nonlinear relation.

C. *Evaluation the performance of the MASs*

To compare the two sensors, graphs are presented in the same domain with the EMG, as seen in Fig.7. The activated region of three sensors is approximately the same, but the start and end points are slightly different. When the muscle is activated, the EMG is activated first and pMAS and oMAS is activated at nearly same time; the muscle activation point of the pMAS signal is clearer than that of the oMAS due to it rapidly increasing.

V. CONCLUSION

In this study, we propose novel methods for measuring muscle activation. pMAS measures the circumference changes of the muscle, one of the processes during muscle activation, and oMAS measures the density of the muscle bundle. Upper limb motions are estimated in order to evaluate the performance of the sensors. The experimental results for each sensor show the relation between the sensor signal and the elbow angles.

The pMAS has advantages in terms of intuitive results and linearity to movement. However, the pMAS can measure several muscles simultaneously and can be applied to limbs that have a dominant muscle effect such as the arms and upper thighs. And oMAS, as it can detect each muscle separately and clearly, it can also be applied to more complex motions such as wrist motion in conjunction with pattern recognition techniques.

In future work some remaining challenges will be addressed. Using the oMAS, wrist motion will be classified to read the user's motion intention. We plan to carry out research on force estimation using these muscle activation sensors and also will attempt to define a velocity related term during the estimation, because estimation of body motion is related to not only positions but also to force and velocity.

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