A Wearable Wireless Apparatus for Sport Equipment

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***Abstract*—Surface electromyogram (sEMG) is an important measurement for monitoring exercise and fitness. With a high sampling frequency requirement, wireless transmission of sEMG is a challenge. Muscle fatigue detection is an important application of sEMG. Traditional muscle fatigue is detected from the median frequency of sEMG power spectrum. Regression slope of the linear regression of median frequency is an important muscle fatigue index. A more negative slope value represents a higher muscle fatigue condition. In this study, a wearable wireless apparatus was developed which could acquire sEMG with a sampling frequency of 2K Hz based upon an MSP 430 microcontroller and Bluetooth transmission. Standard Isotonic and isometric muscle contraction are clearly represented in the receiving user's interface. The median frequency of sEMG power spectrum was used to detect the muscle fatigue. To test this apparatus performance, 10 subjects ran an elliptical trainer for approximately 30 minutes at three loading levels. Results show that the wearable wireless apparatus can monitor the muscle fatigue when users are sporting.**

I. Introduction

Health care has been paid attention at today. Many people have known more exercise, more health. Many people living in the modern city use the sport equipment to do exercise because they lack time and place to exercise. However, the muscle fatigue easily gets exercising injury when users don't correctly use sport equipment. How to monitor user's sporting condition to avoid over exercise is an important study. Physiological monitoring with wireless transmission can be applied to many applications [1], such as healthcare monitoring with portable devices [2]. Among these physiological measurement systems, EMG is an important non-invasive measurement for monitoring muscle fatigue.

Surface electromyogram (sEMG) is measured by electrodes attached to the surface of the skin, above the muscle of interest. There are many novel application based upon sEMG. Such as for upper limb prosthesis control [3], exercise and fitness monitoring [4, 5]. There are a variety of articles involved with muscle fatigue detection by sEMG amplitude and frequency [6, 7]. The advantages of sEMG are the non-invasiveness and real-time fatigue monitoring during the performance of defined work; it can also monitor the fatigue of a particular muscle that is highly correlated with biochemical and physiological changes in muscles during fatiguing. Power spectrum analysis is the main EMG signal analysis method. Spectral parameters such as mean frequency (MNF) and median frequency (MF) are used as fatigue indices during dynamic contractions until exhaustion. The MNF and MF always shift to the low frequency when muscle fatigue has occurred.

Although muscle fatigue is one of the important applications of sEMG measurement, along with the need for exercise and rehabilitation programs, there are still few sEMG recording systems with appropriate wireless transmission functions. The main problem is the high transmission rate. In general, the sample frequency for measuring sEMG is above 1k Hz [8]. If MNF is used to evaluate muscle fatigue, the sample frequency must be 2k Hz. Therefore, the goal of this study is to develop a wireless sEMG recording system with a 2k Hz sample rate for muscle fatigue estimation.

II. Method

The structure of this wireless EMG recording and muscle fatigue detection system is illustrated in Figure 1. This system is based on the microcontroller MSP430-F5342 as the core structure. The EMG signal is recorded from electrodes attached to the subject and transmitted to the amplifier circuit. The surface electrodes used for the EMG recording were Ag/AgCl 10mm diameter on self-adhesive supports, and inter-electrode distance was 2.5 cm. A microcontroller converts the recorded data to a digital signal through a 12-bit analog-to-digital converter (ADC) embedded in MSP430-F5342. The digital EMG signal is then transferred to a Bluetooth chip and transmitted wirelessly to a remote server. A Visual Basic-based interface system is used to receive the Bluetooth signal and is also used as a real-time signal display and storage. Further EMG signal analysis is performed by a Matlab coded program.

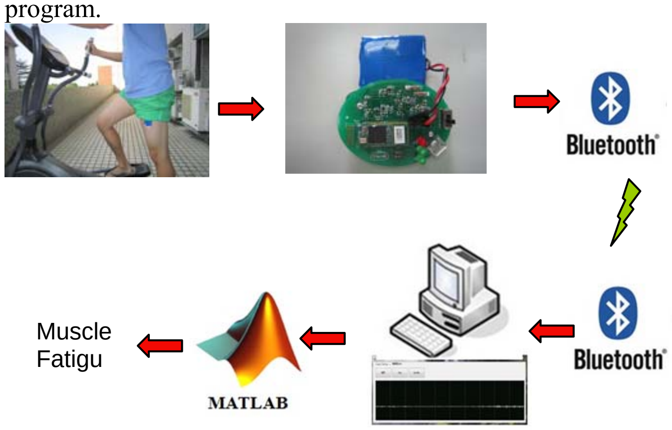

Fig. 1. Structure of wireless sEMG recording and muscle fatigue detection and estimation system.

A. sEMG Sensor and Amplifier

The raw sEMG signal is a low-amplitude signal; therefore, it needs to be amplified. An instrument amplifier (AD8236, ADI Company), with a gain of 10, is used to enhance the signal. A traditional operational amplifier (AD 8609, ADI Company) is used in the design of a filter, amplifier, peak rectifier, and baseline offset circuit. A two-order Butterworth high-pass filter (cutoff frequency 30Hz) is used to remove the direct current (DC) offset and baseline wandering, and a two-order Butterworth low-pass filter (cutoff frequency 1k Hz) is used to reduce high frequency noise and to avoid aliasing. The gain of the non-inverting amplifier is 100. The peak rectifier, a parallel circuit of a resister (10k Ω) and a capacitor (1μ F), is used to extract the envelope of the sEMG as an appropriate measure of change in muscle activity. Finally, the baseline of sEMG signal was raised to 1 V by a baseline offset circuit. The power supply for the measurement system is a 4.5-V lithium battery. A voltage regulator (XC62FP) is used to provide a regulated 3.3 volts for this circuit.

B. Transmission

The sampling frequency is 2k Hz. The MCU used the serial communication port (baud rate: 115,200) to connect to the Bluetooth module. Because the A/D converter of the MCU is 12 bits, the sample data were separated into low and high bytes. Therefore, in one sample point, there are two sample data from the sEMG and its envelope which are separated by 4 bytes and stored in a buffer. In this device, when the Bluetooth is suddenly interrupted and communication stopped, some bytes are still being stored in the Bluetooth buffer, and when the Bluetooth transmits data again, these bytes would appear before the new data. Hence, we transmitted 2 bytes, FF and FF, as the distinguishing code before the 4 sample data to distinguish each sample point's data, as shown in the transmitted form of Figure 2(a). When the Bluetooth model received the data, 6 bytes were considered as a segment. We first found the position of the distinguishing code. Then, one sample point's data would be acquired between two distinguishing codes, as shown in the received form of Figure 2(b).

1	2	3	4	5	6
0xFF	0xFF	EMG_H	EMG_L	Envelope_H	Envelop_L

(a) Transmitted

		1	2	3	4
Envelope_H	Envelope_L	0xFF	0xFF	EMG_H	EMG_L

5	6				
Envelop_H	Envelop_L	0xFF	0xFF	EMG_H	EMG_L

(b) Received

Fig. 2. Data transmitting and data receiving modes in the Bluetooth protocol.

C. User Interface

A remote personal computer (PC) receives the Bluetooth-transmitted data and connects to the host PC through Universal Telecommunication Radio Access (UTRA). A Visual Basic-based user interface was designed to collect the data package from the Bluetooth device through a serial COM port. Transmitted sEMG and its envelope signals were examined and displayed on a monitor. Offline sEMG signal analysis was performed, and the data was saved in a text file format. Figure 3 is the received sEMG and its envelope signal.

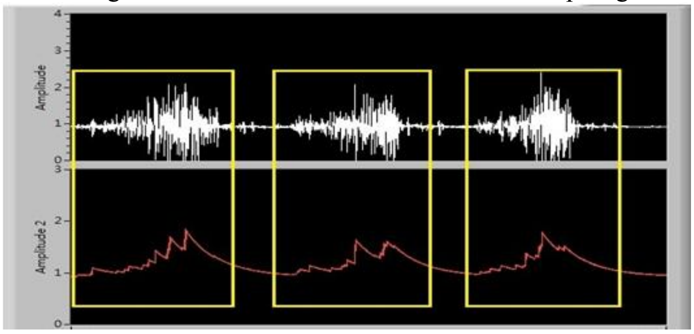

Fig. 3. Display of the received EMG signal. The isotonic contraction signal (upper waveform) and corresponding waveform envelope (lower waveform).

To test the sEMG hardware performance, a dumbbell of 20 pounds was held for one minute. In Figure 4(a), periodic muscle contraction is obvious with the isotonic contraction exercise. Figure 4(b) is the result of isometric contractions. It is obvious that this portable sEMG system is capable of recording muscle contraction effectively.

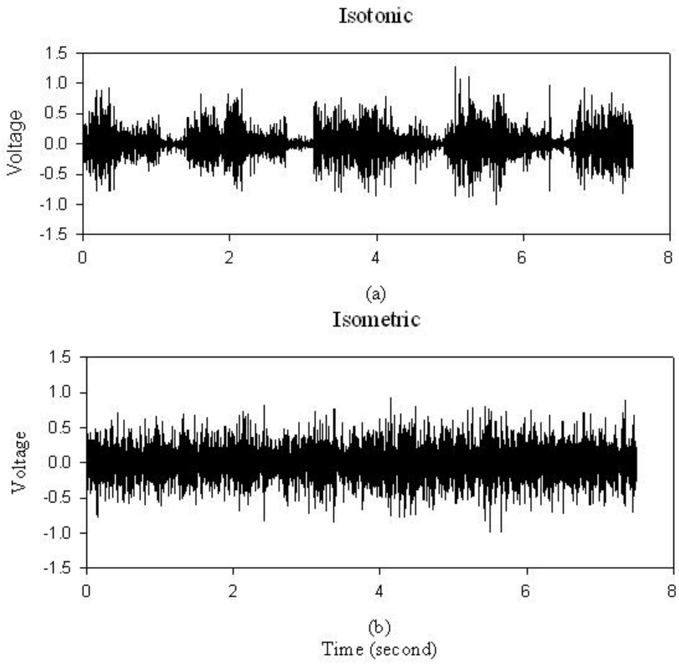

Fig. 4. sEMG hardware performance examination for (a) 7.5 seconds isotonic contraction. (b) 7.5 seconds isometric contraction

D. Experiment Procedure

There were ten volunteers involved (5 male, and 5 female), with ages ranging from 19 to 27 years. Their information is listed in Table 1. Before data collection, a consent form was signed by each subject. The developed wireless sEMG device is worn on the lateral waist. The upper edge of left patella was used as the reference point. Electrodes are placed at 15 cm position above the reference point, and close to the medium of left vastus lateralis, as shown in Fig. 5. The sEMG data is transmitted to the host computer and recorded. The subjects were required to run on the pedaled-multifunctional elliptical trainer (Johnson E8000) for monitoring their muscle fatigue conditions.

TABLE I
Subject characteristics

Variable	Male (n=5)	Female (n=5)	P value
Age (years)	24 (2)	21 (2)	0.13
Weight (Kg)	78.6(10.8)	53.3(5.3)	0.0015**
Height (cm)	176.5(6.8)	163.6(4.7)	0.0078**
BMI (Kg-M^{-2})	25.0(3.9)	19.8(1.4)	0.02*

Data are expressed as mean (standard deviation). BMI is Body Mass Index. P <0.05*; p<0.01**

Fig. 5. Illustration of wearable wireless sEMG device worn on the lateral waist with electrodes placed on the left vastus lateralis.

An exercise based muscle fatigue examination procedure was established as follows:

Step 1: Subjects wear the wireless sEMG device during the procedure. Alcohol is used to clean the electrode surface prior to smearing electrolytic gel on the electrodes to decrease contact impedance. Athletic tape is used to fix the electrodes and so to avoid movement of the electrodes.

Step 2: There are three load levels in the pedaled-multifunctional elliptical trainer, L2, L4 and L6, with L2 being light and L6 being heavy. The speed of L2 is 55-60 step per minute (SPM) for male and 50-55 for female. The speed of L4 is 60-70 SPM for male and 56-65 for female. The subjects were required to run at their maximum speed until exhaustion on L6, the speed being greater than that on L4. Ten minutes is the set time for both for L2 and L4.

Step 3: Each subject was recorded twice a week, and there were a total of six recording times for each subject.

E. Muscle Signal Processing

The recorded sEMG is divided into many segments and a Fast Fourier Transform is performed. The MF of each segment is extracted. MF is defined as the frequency where the accumulated spectrum energy is half of the total spectrum energy, as shown in equation (1). Where *p(f)* is the power spectrum density of sEMG.

$$\int_0^{MF} p(f)df = \int_{MF}^{\infty} p(f)df = \frac{1}{2}\int_0^{\infty} p(f)df \qquad (1)$$

The window size of the sEMG segment is 30 seconds, and step size is 15 seconds. In order to quantify the distribution of MF during the examination of three stages, a linear regression analysis was applied to evaluate the muscle fatigue condition [9]. The linear function is defined as:

$$y = Ax + b \qquad (2)$$

where y is MF and x is the time interval, A is the regression slope and b is the bias. The greater the muscle fatigue, the smaller the slope [9]. We also used the correlation coefficient (r) to represent the stability of sEMG in terms of muscle fatigue, which is defined as:

$$r = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}} \qquad (3)$$

where $\bar{x}$ and $\bar{y}$ are average of x and y, respectively. In this study, x is time and y is MF frequency. The more stable sEMG, the larger the r value is. A typical MF distribution is shown in Fig. 6. It is well known that MF will decrease as muscle exercise time increases. Parameter r and A will be used to describe the variability and degree of muscle fatigue.

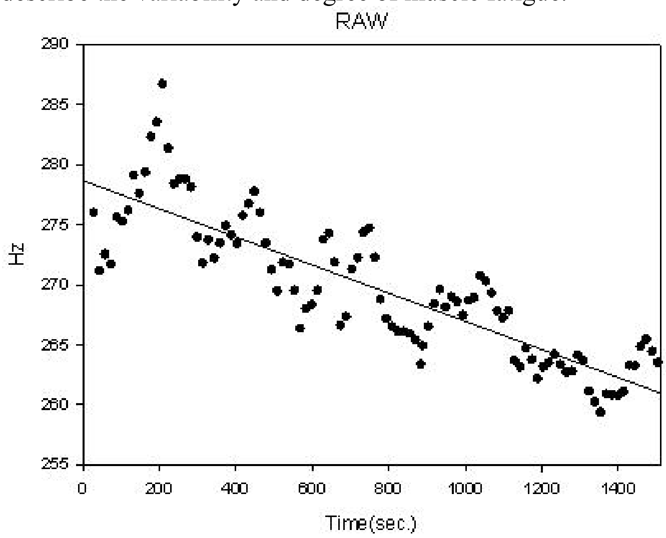

Fig. 7. A typical illustration of median frequency distribution and regression line for one subject for 30 minutes exercise.

F. Statistics

In this study, the SIGMAPLOT software package was used for data analysis. Descriptive statistics were applied to subjects' personal information and muscle fatigue parameters (regression slope and correlation coefficient). Data were represented as mean ± standard deviation (mean ± SD). Statistical testing between male and female on muscle fatigue parameters was examined by t-test. Significance test for the alpha value was set at 0.05.

III. RESULTS

The MF regression parameters distribution for 30 minutes of exercise is shown in TABLE I. There is a significant gender difference for muscle fatigue as seen in the regression slope during L4 (male -0.0088±0.0070, female -0.0161±0.0113, $p<0.01$**) and L6 (male -0.0128±0.0095, female -0.0257±0.0175, $p<0.001$***), and also during L2 (male 0.6079±0.2366, female 0.4192±0.2774, $p<0.01$**), L4 (male 0.4912±0.2259, female 0.6383±0.2196, $p<0.05$*) and L6 (male 0.5080±0.2220, female 0.6393±0.2729, $p<0.05$*) load level with correlation coefficient parameter. There is no gender difference on both parameters for the whole 30 minute session. A lower slope is an index of higher muscle fatigue. At the beginning of the experiment (L2 session), the slope between gender is very close and there is no statistical difference. During the exercise time, the slope for females is lower than that of males.

TABLE II
Slope and Regression results of muscle fatigue examination for gender difference. Data are expressed as mean (standard deviation).

Parameters	levels	Male (n=30)	female (n=30)	P value
Slope (A)	L2	-0.0167 (0.0108)	-0.0160 (0.0175)	0.859
	L4	-0.0088 (0.0070)	-0.0161 (0.0113)	0.004**
	L6	-0.0128 (0.0095)	-0.0257 (0.0175)	0.0008***
	All	-0.0170 (0.0121)	-0.0224 (0.0130)	0.098
Correlation coefficient (r)	L2	0.6079 (0.2366)	0.4192 (0.2774)	0.006**
	L4	0.4912 (0.2259)	0.6383 (0.2196)	0.013*
	L6	0.5080 (0.2220)	0.6393 (0.2729)	0.045*
	All	0.8154 (0.1910)	0.8246 (0.1824)	0.849

TABLE III
Slope and Regression result of muscle fatigue examination for all subjects. P value is test result of t-test. Data are expressed as mean (standard deviation).

levels	Slope (A)	p-value	Correlation coefficient (r)	p-value
L2	-0.0164 (0.0144)	vs.L4=0.08 vs.L6=0.28	0.5136 (0.2727)	vs.L4=0.27 vs.L6=0.21
L4	-0.0125 (0.0100)	vs.L6=0.0047**	0.5647 (0.2330)	vs.L6=0.84
L6	-0.0193 (0.0154)	N.A.	0.5737 (0.2554)	N.A.
ALL	-0.0197 (0.0128)	N.A.	0.8200 (0.1852)	N.A.

VI. Discussion and Conclusion

With the EMG signal being around 100-1000 Hz, wireless EMG transmission is not easy to accomplish due to the high frequency components. According to Nyquist's theory, sampling frequency must be twice as high as the maximum signal frequency. Wireless transmission capacity is the limiting factor for sampling frequency. With a suitable arrangement of MSP430 and the Bluetooth chip, this proposed system is able to achieve a satisfactory sampling frequency of 2000 Hz. The advantage of this system is the high sampling rate (2000Hz) than that of most commercial wireless EMG recording system (around 1000 Hz or below) [10]. It is expected to achieve sufficient sampling rate to meet the high frequency range of sEMG. Combined with MSP430 and Bluetooth system, the proposed sEMG recording is stable, low cost, low power and user friendly. Bluetooth transmission is often interrupted, due to environmental electromagnetic wave interference or concrete structure blockage. This system can record sEMG data with its envelope being stored in a buffer. When the Bluetooth is suddenly interrupted and communication stopped, buffered data will be transmitted when the system is reconnected.

The well-known phenomenon of MF decreasing with muscle fatigue increasing is also demonstrated with this system. Females will suffer more muscle fatigue when exercising. This is also shown in the results with the MF regression slope for females being lower than for males. The gender difference is significant on each 10 minute session at L4 and L6 levels. L6 level is the maximum voluntary contraction. Thus, its mean slope is smaller than the other levels, and there is a significant difference from the mean slope of L4 level, in Table 3. Although, for the correlation coefficient, the gender difference is also significant on levels L2 to L6 in Table 2, we could not find a relationship between the stability of sEMG and the force level, as shown in Table 3. This phenomenon is the same as in previous studies [8]. Moreover, in Table 3, we find that the mean slope of the L2 level is lower than that of the L4 level, and its standard deviation is larger than that of the L4 level. The reason for this is that the L2 level is the minimum voluntary contraction, and belongs to the beginning of the exercise. Thus, the degree of muscle fatigue is very light. In Figure 7, the MF distribution of the L2 level does not decrease gradually. This phenomenon has also been reported in previous studies [8].

A wearable wireless apparatus has been developed to monitor the muscle contraction activity. A high sampling frequency achieving 2 kHz of Bluetooth transmission is beneficial for walking and exercising. The standard muscle fatigue index, the regression coefficient, and slope of MF for three loading exercises were also examined. According to our experiment, this wearable wireless apparatus can monitor the muscle fatigue when users are sporting.

Acknowledgment

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