Design of Muscular Bioimpedance Measurement System

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Abstract. A design scheme of multi-channel muscular bioelectrical impedance measurement system for monitoring muscle fatigue is proposed. The system consists of three major parts: electrode array, switch matrix and bioimpedance measurement unit. The system collects signals on electrode array through the switch matrix, and the integrated impedance measurement IC AD5933 is used for extract the bioelectrical impedance of muscle. The MCU (Microcontroller Unit) controls the system and communicates with the host computer. The system can monitor the bioimpedance changes during human motion in real time and provide early warning of impending muscle damage.

Introduction

Bioelectrical impedance analysis (BIA) technology is a non-invasive detection technology that extracts biomedical information related to human physiological and pathological conditions by utilizing the electrical properties (impedance, admittance, dielectric constant, etc.) and changes of biological tissues and organs. BIA technology has attracted extensive attention and become a research hotspot because of its non-invasive, low cost, sustainable detection, non-electromagnetic radiation and radioactivity[1,2,3].

Previous studies have shown that skeletal muscle fatigue has a significant correlation with its bioelectrical impedance[4], and the rapid decline of skeletal muscle’s bioimpedance can be used as an early warning signal of muscle injury. G. Vescio et al. performed five sets of strength exercises on the subjects, and measured the skeletal muscle’s impedance at multiple frequencies using the four-electrode method. The measurement results showed that the impedance of the first three times increased at different frequencies, and the impedance model of the fifth time was obvious decline [5]. Takuto Ikai et al. used an impedance analyzer to take a four-cycle measurement of 25-second bending motion of the biceps, a 5-second rest. The same initial impedance increase followed by a decrease [6]. The above studies have shown that monitoring the muscle electrical impedance before and after exercise can determine the degree of muscle fatigue.

Designing and manufacturing a portable muscle fatigue monitor device has a great significance in preventing muscle damage during physical training. If there is a small instrument that can detect changes in muscle electrical impedance during the training interval, user can monitor the changes in the body in advance and prevent muscle injury.

Materials and Methods

In order to collect multi-channel body impedance information, the flexible electrode array is attached to the upper arm or thigh to collect the electrical impedance signal, and is connected to the measurement board with a 24-pin socket[7,8], then the integrated chip AD5933 are used as impedance measurement unit. Two ADG2128 chips are performed as measurement channel switch, which is controlled by MCU STC12C5A60S2. The MCU is also used in communicating with the host computer. The overall design is showed in Fig. 1.
According to the relevant literature and previous experimental measurements, the surface impedance of the human body is on the order of 10kΩ. Depending on the roughness of the skin, different body impedances are concentrated in the 10kΩ to 40kΩ range at rest. As the blood flow increases during exercise, the body's impedance decreases, and the lowest value can be close to 5kΩ. Therefore, the AD5933 range of 1kΩ to 1MΩ meets the experimental requirements, and the maximum 2V peak-to-peak value generated by the AD5933 meets the human safety voltage requirements.

The channel switching circuit consisting of two ADG2128 chips has an on-resistance of less than 35Ω, an on-time of less than 260ns, a quiescent current of less than 20μA, and a bandwidth of 300MHz to meet system requirements.

**Electrode Array**

There are 24 copper electrodes fabricated on a flexible circuit board with a spacing of 1.5 cm between adjacent electrodes. The carrier was a polyimide having a thickness of 150 μm, and the single electrode was a copper sheet having a diameter of 3 mm and a thickness of 300 μm. In order to stabilize the contact resistance between the skin and the electrode, the surface of the copper electrode was plated with a thickness of 2 μm of nickel and a gold plating layer of 0.035 μm thickness by electroplating. The 24 electrodes form a 4×6 electrode matrix. The laterally adjacent electrodes are a group, and a total of 12 sets of signals are formed. The electrode array is separated from the measuring circuit board, so that the change of the electrode arrangement mode does not affect the overall design of the circuit board, thereby enhancing the adaptability of the system. The flexible electrode array PCB layout is shown in Fig. 2.
Data Processing Circuit

The signal connected by the switch matrix is filtered by the op amp chip OPA2350 and peripheral circuits and then connected to the measuring ports of the Analog Devices’ AD5933 chip. The AD5933 is a high precision impedance converter system solution with an on-chip integrated frequency generator and a 12-bit, 1M sps analog-to-digital converter (ADC) that uses a signal generated by a frequency generator to excite an external complex impedance. The external impedance response is sampled by the on-chip ADC. Then, Discrete Fourier Transform (DFT) processing is performed by the on-chip DSP. The DFT algorithm returns a real (R) data word and an imaginary (I) data word at every scan frequency point. The impedance magnitude and phase are easily calculated using the following formula:

\[
\text{magnitude} = \sqrt{R^2 + I^2} \\
\text{Phase} = \tan^{-1}\left(\frac{I}{R}\right)
\]

The schematic of the data processing circuit is shown in Fig. 3.

System Evaluation

Four standard resistors with resistance values of 1KΩ, 10KΩ, 100KΩ, and 1MΩ were selected, and the four standard resistors were measured ten times using the designed system. The measurement results are shown in the fig. 4. From the measurement results, in the three sets of measurements of 1KΩ, 10KΩ, and 100KΩ, the error between the measured value and the standard value of the system is within 1%, and the measurement results are consistent. During the measurement of 1MΩ, the fluctuation of the measured value is slightly increased, the error between the measured value of the system and the standard value is within 2%. The error may be caused by the interference of the environmental resistance.

We selected a healthy person to measure the impedance of bicipital muscle of arm, which hold load of 10kg. The test select 5 channels of 12 channels(Channel A/C/F/H/K), and read the magnitude and phase of bioimpedance every 20s. The results are shown in Fig. 5. It can be clearly observed that as the fatigue of the muscle increases, the magnitude and phase of bioimpedance show a downward trend. In the range of body bioimpedance, the system has a measurement accuracy of less than 1%, and the measurement time is less than 0.1ms. From the measurement result, it can be seen that our system has potential for muscle fatigue monitoring.
Conclusions

We proposed a design scheme for measuring the muscular bioelectrical impedance, which adopts a flexible PCB to fabricate a skin electrode array, and switches the amplifying channel through a switch matrix device. The impedance measuring chip is used to measure the bioimpedance of the muscle. The measured results are transmitted through the communication chip to the host computer and finally obtains multi-channel impedance measurement data. From the system evaluation result, it can be seen that the measurement error of our system is within 2%, which has potential for muscle fatigue monitoring.

References


