CONTINUOUS MONITORING OF MUSCLE THICKNESS CHANGES DURING ISOMETRIC CONTRACTION USING A WEARABLE ULTRASONIC SENSOR

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ABSTRACT

We investigated the continuous monitoring of muscle thickness during muscle contraction using a wearable ultrasonic sensor. This sensor enables muscle monitoring without restricting muscle movement beneath the sensor due to its lightness, thinness and flexibility. In the *in vivo* experiment conducted in this study, M-mode ultrasound measurements were performed on the right forearm of a human subject. For the isometric muscle contraction performed in the experiment, the measured average total thickness change of the tissue between the sensor (skin surface) and bone was 0.8 mm (3.4%). In addition, it was successfully demonstrated that the thickness change of each muscle layer was measured in accordance with the performed muscle contraction.

INTRODUCTION

Skeletal muscle contraction and relaxation causes changes in the physical parameter of muscles such as its thickness, length, tension, stiffness and density [1-3]. Measurements of these parameters during body physical activity could provide useful information for various medical and clinical applications. For example, it has been reported that muscle fatigue could be assessed by monitoring the muscle thickness change during contraction [4].

There are several techniques used to study muscle activities, such as surface electromyography (sEMG) [5-10], magnetic resonance imaging (MRI) [11-13] and ultrasound [4,14-20]. sEMG measures the small electrical current or signal arising from active muscles, using electrodes directly placed on the skin above the muscles of interest. This technique is used to determine the muscle force, length [5,6] and action potential conduction velocity non-invasively [7-9]. MRI is also a useful technique to study muscles activities. However, its non-portability and high-cost make it undesirable for use with large number of subjects or monitoring of large muscle motion.

Ultrasound is a non-invasive, harmless and relatively low-cost technique. It can observe the structure and motion of muscles and other tissues in real-time with a high frame rate. Ultrasonic methods have been applied for diagnosis of neuromuscular disorders [14,15] and injury [16], assessment of muscle fatigue [4] and monitoring of muscle motion [17,18]. However, one of the challenges for monitoring muscle activities is the motion artifacts caused by random movements of the employed ultrasonic probe, which reduces the measurement accuracy [19]. In addition, the probe pressed against a body surface may limit underlying muscle activities.

In order to overcome these issues, we have developed a film-type ultrasonic sensor using a piezoelectric polymer transducer [21]. This sensor is light, thin and flexible so that the sensor is wearable. It enables muscle monitoring without restricting muscle movement beneath the sensor when attached to the body surface of a subject. Such feature is not available with a conventional handheld ultrasonic probe due to its bulkiness. In this paper, we have investigated the feasibility of continuous monitoring of muscle thickness during isometric contraction using the developed wearable ultrasonic sensor.

METHODOLOGY

Measurement Model

Figure 1 depicts a schematic of the measurement model of tissue thicknesses with an ultrasonic pulse-echo technique. A measured object is composed of several soft tissue layers such as skin, fat and muscle with bone at the bottom. An ultrasonic sensor is attached onto the skin surface of the subject. Pulsed ultrasound is transmitted into the subject and reflected from the tissue boundaries. The reflected signal is received by the same ultrasonic sensor. The depth (distance) of the tissue boundary from the ultrasonic sensor (skin surface) can be obtained by measuring the time-of-flight (Δt) of the reflected signal with the known ultrasound propagation speed (v) in the tissues. Then, the thickness (h) of each tissue can be calculated by: $h=v\Delta t/2$.

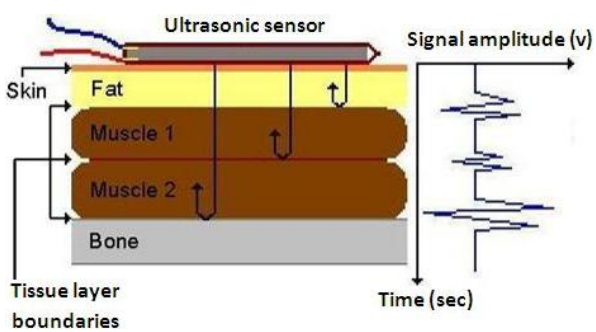

Figure 1: Schematic of the measurement model of tissue thickness.

Ultrasonic Sensor

A photograph of the wearable ultrasonic sensor used in this study is presented in Figure 2. The sensor was attached onto the right forearm close to the elbow of a male subject with ultrasonic gel couplant. The sensor was fixed using adhesive tape. The total thickness of the sensor was 0.2 mm and the weight was less than 1 g. The ultrasonic active area of the sensor was 15 mm by 15 mm which is the overlapped region of the top and bottom electrodes of the sensor. The design and construction of this sensor were given in [21].

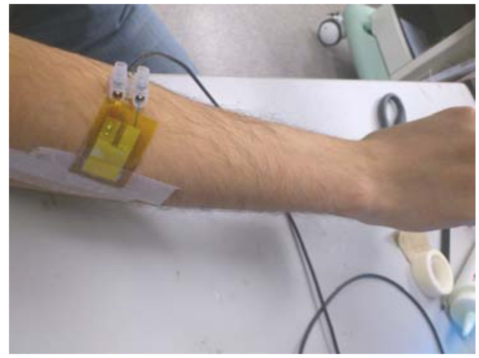

Figure 2: Wearable ultrasonic sensor attached onto a right forearm.

Signal Acquisition

The ultrasonic sensor was connected to an ultrasonic pulser/receiver (Model: DPR300, JSR Ultrasonics, Pittsford, NY) to transmit and receive ultrasound in a pulse-echo mode. The ultrasonic signals reflected from tissue boundaries were acquired using a 12-bit PCI digitizer (Model: ATS420, AlazarTech, Montreal, QC, Canada) with the sampling frequency of 125 MHz. During the signal acquisition, isometric contraction of the forearm muscles beneath the sensor was performed by clenching and relaxing the right hand alternately for 10 seconds with the transition interval of 2 seconds. The signals were acquired for total 60 seconds in M-mode ultrasound measurement.

RESULTS AND DISCUSSIONS

A result of the M-mode measurement during isometric muscle contraction is shown in Figure 3. The grayscale level indicates the amplitude of the received ultrasonic signals. The darker gray represents the greater amplitude of the signals. Four ultrasonic signals, denoted by B1, B2, B3 and B4, were observed, which probably correspond to the boundary of fat-muscle (T1-T2), muscle-muscle (T2-T3), muscle-muscle (T3-T4) and muscle (T4)-bone, respectively. It is seen that the depth of each boundary changed with accordance of muscle contraction and relaxation. It is noted that the tissue types could be identified more accurately by means of B-mode ultrasonic imaging, which was not available with the presented sensor and measurement configuration employed in this study.

From the time-of-flight of received ultrasonic signals, the depth of each layer can be obtained using the known ultrasound speed in the tissues. A cross correlation technique is often used to determine the time difference of signals. However, it was found that the cross correlation technique directly applied on the raw ultrasonic signals in Figure 3 did not result in accurate estimation of the time-of-flight. The estimation accuracy was reduced when the shape, amplitude and frequency components of the signals changed during muscle contraction due to muscle lateral motion, tissue boundary inclination, signal interference with speckle echoes, and random noise.

Therefore, the Fourier transform was first applied on received ultrasonic signals of each boundary and the narrowband signals at a chosen frequency within the bandwidth of the signals were reconstructed by inverse Fourier transform. Then, the cross correlation technique was used to determine the difference of the time-of-flight between two consecutive signals reconstructed for each boundary. The results of the boundary depths are shown in Figure 4. It is seen from the depth of the B4 (bone boundary) in Figure 4 that the total tissue thickness changed from minimum of 22.8 mm to maximum of 24.2 mm. The average thicknesses in the relaxed and contracted states were 23.2 mm and 24.0 mm, respectively. Thus, the average thickness change due to muscle contraction performed in this experiment was 0.8 mm (3.4%).

The tissue thicknesses obtained from the results of the boundary depths in Figure 4 are shown in Figure 5. It was presumed that the tissue T1 was fat and the tissues T2, T3 and T4 were muscles. It was observed that the thicknesses of the muscle tissues (T2, T3, T4) increased in the contraction state compared to the relaxed state. On the other hand, the thickness of the fat tissue (T1) decreased in the contraction state since the fat layer was compressed by the muscles expanding during contraction. The maximum thickness changes due to contraction were −12%, 15%, 26% and 21% for T1, T2, T3 and T4, respectively.

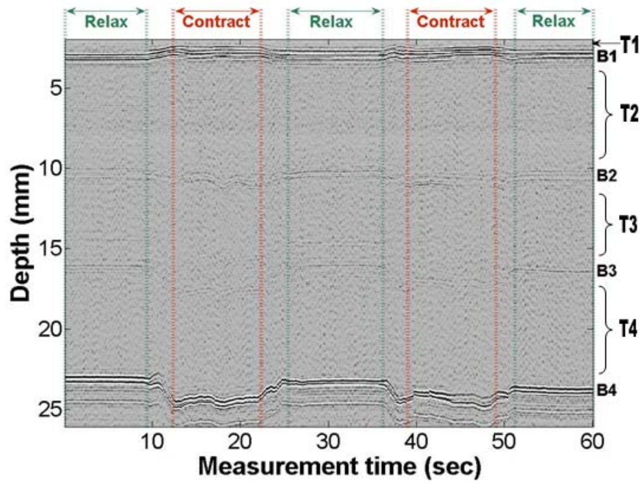

Figure 3: A result of M-mode ultrasound measurement at forearm.

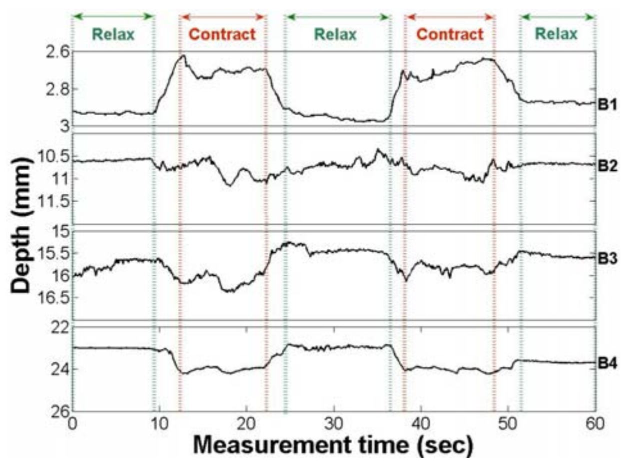

Figure 4: Depths of tissue boundaries obtained from the measured result in Figure 3.

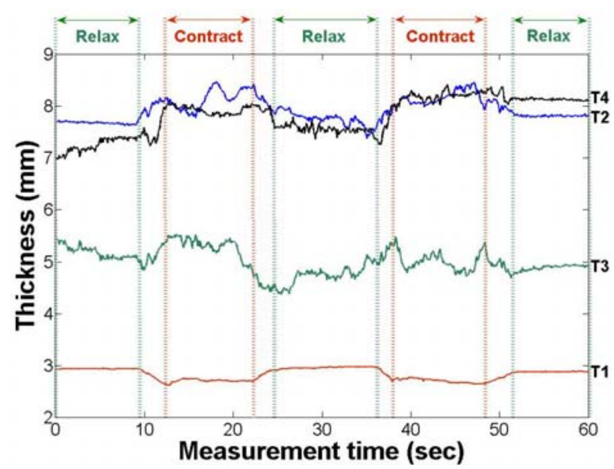

Figure 5: Tissue thickness changes obtained during muscle contraction and relaxation.

SUMMARY

It was successfully demonstrated that thickness changes of muscles in a subject's forearm in accordance with the isometric contraction were quantitatively obtained using a developed wearable ultrasonic sensor by means of an ultrasonic time-of-flight method. This wearable ultrasonic sensor could enable real-time and continuous muscle monitoring during various physical activities.

In future study, improvement and verification of the measurement accuracy of the proposed technique will be investigated with numerical simulation and phantom experiments. Furthermore, measurements of muscle thickness in various body locations of interest and with different muscle types will be performed. The comparison between subjects with and without muscular diseases will be also conducted.

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