Internal muscle activity imaging from multi-channel surface EMG recordings: a validation study

Yang Liu, Yong Ning, Jinbao He, Sheng Li, Ping Zhou-*IEEE Senior Member* and Yingchun Zhang-*IEEE Senior Member*

Abstract— **The developed muscle activity imaging approach (MAI) was validated with surface EMG and intramuscular EMG signals simultaneously acquired from the biceps of a healthy male subject. 128 unipolar channels were employed for surface EMG measurement and one bipolar channel was employed for simultaneous intramuscular EMG measurement for the validation purpose. Ultrasound scans were also specifically performed to localize the location of the wire electrode inserted into the biceps. The surface EMG measurements, after noise filtering and signal decomposition, were used to reconstruct the internal muscle activities for the biceps by using the MAI approach. The locations of the reconstructed muscle activities were compared against the location of the wire electrode in the biceps identified from ultrasound images. Results demonstrate the feasibility and validity of the MAI approach in imaging internal muscle activities from multi-channel surface EMG recordings.**

I. Introduction

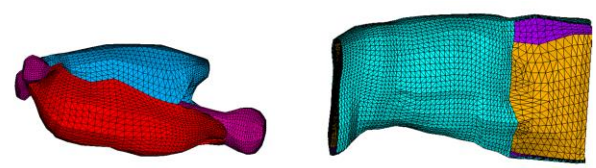
Muscle unit action potentials (MUAPs) are generated at the neuromuscular junction or end-plate, and propagate bi-directionally toward the tendon endings of each fiber where they become extinguished. The shapes and firing rates of MUAPs in electromyography (EMG) signals provide an important source of information for the diagnosis of neuromuscular disorders [1-3]. Surface EMG and intramuscular (needle and fine-wire) EMG are two kinds of EMG in widespread use for muscle activity recording. To perform intramuscular EMG, a single fiber, monopolar concentric or a macro needle electrode [4-5] is inserted to the muscle to be studied to record muscle activities of a few fibers. Intramuscular EMG is usually painful and may be traumatic, especially for children. The surface EMG is a non-invasive technique to measure muscle activity by placing electrodes on the skin overlying a muscle or group of muscles [6-7], but its poor spatial resolution and specificity limits its application in clinic. A muscle activity imaging (MAI) approach was recently developed [8] to overcome the limitation of the surface EMG technique by characterizing the specific muscle groups which are responsible for the discharged surface EMG.

In the present study, the feasibility and validity of the MAI approach in imaging internal muscle activities were tested with 128-channel surface EMG and intramuscular EMG recordings simultaneously acquired from the biceps of a healthy male subject.

II. Methodology

A. Upper arm model

A subject-specific upper arm model constructed from MR and ultrasound images includes skin, fat, biceps, triceps, compact bone and cancellous bone. The model was meshed with ANSYS 13.0 (ANSYS, Canonsburg, PA) into a finite element model for computation as shown in Figure 1. The entire finite element model of the upper arm consists of 225,462 tetrahedron elements and 39,605 nodes. The conductivity values assigned to the skin, fat, muscle, compact bone and cancellous bone were 4.55×10^{-4} S/m, 0.0379 S/m, 0.2455 S/m, 0.02 S/m and 0.075 S/m, respectively [9].



(a) (b)

Figure 1. Computation model of (a) the bones and muscles, and (b) the entire upper arm.

The composite 128-channel surface EMG signals were decomposed by using our newly developed K-means clustering and Convolution Kernel Compensation (KmCKC) method [10]. A total of 10 innervation pulse trains (IPTs) were successfully decomposed from the surface EMG signals. Accordingly, ten motor unit action potential (MUAP) trains were successfully reconstructed from the decomposed IPTs. The cross-correlation between each reconstructed MUAP train and the simultaneously recorded intramuscular EMG recording was calculated. A good cross-correlation indicates that the MUAP trains decomposed from the surface EMG signals and the simultaneously recorded intramuscular EMG signal caught the muscle activities generated by the same motor unit (MU). The correlation calculation results show that the 3rd MUAP train has the best correlation with the intramuscular EMG signal. The decomposed 128-channel

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Y. Liu, Y. Ning and J. He are with the Biomedical Engineering Department, University of Houston, Houston TX, 77204.

S. Li is with the Department of Physical Medicine and Rehabilitation, University of Texas Health Science Center at Houston, TX, USA

P. Zhou is with the Department of Physical Medicine and Rehabilitation, University of Texas Health Science Center at Houston, USA, and also with the Biomedical Engineering Program, University of Science and Technology of China, Hefei, China

Yingchun Zhang is with the Department of Biomedical Engineering, University of Houston, Houston, TX 77204 USA. (Phone: 713-743-6127; Fax: 713-743-0226; e-mail: yzhang94@uh.edu).

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surface EMG monopolar action potentials and the calculated bipolar action potentials for MU #3 are presented in Figure. 2.

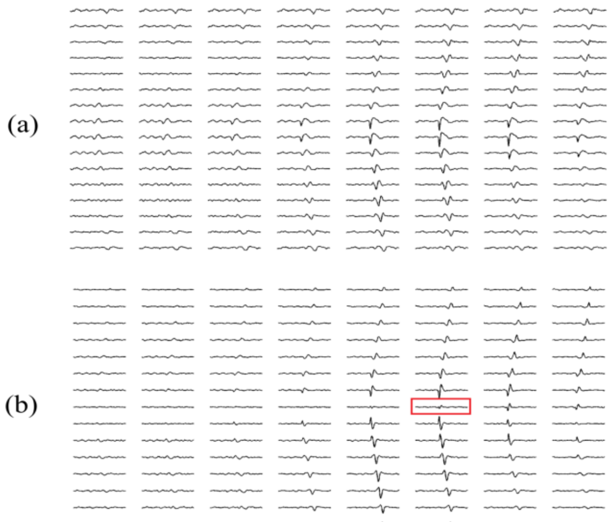
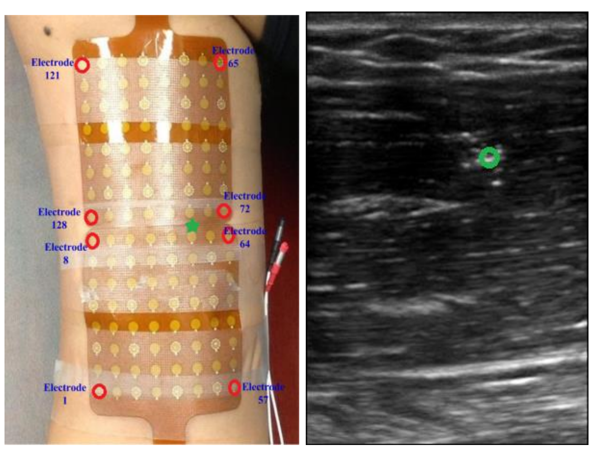


Figure 2. (a) Decomposed 128-channel surface EMG monopolar action potentials and (b) calculated bipolar action potentials of MU #3. The red rectangular in (b) specifies the location of innervation zone of MU #3, which is closest to the 48th surface EMG electrode.

B. Experimental setup

Simultaneous surface EMG and intramuscular EMG measurements were acquired from the biceps of a healthy male subject with a 136-channel Refa (TMSi, Enschede, Netherlands). The 128 unipolar channels were employed for surface EMG measurement and one bipolar channel was employed for simultaneous intramuscular EMG measurement for the validation purpose. A sampling rate of 2 KHz was adopted for both surface and intramuscular EMG recordings. Figure 3(a) shows the relative position of surface EMG



(a) (b)

Figure 3. (a) shows the relative position of surface EMG electrodes and wire electrode (green star) over the subject's right upper arm. (b) shows the location of the wire electrode (green circle) in the ultrasound image of the upper arm.

electrodes and the intramuscular wire electrode (green star) over the subject's right upper arm. Ultrasound scans were also specifically performed to localize the placement of the wire electrode inserted into the biceps (Figure 3(b)).

C. MAI inverse problem

A distributed dipole source model [11] was employed in the MAI approach. A number of 42,840 electrical current dipoles were evenly distributed in the 3-dimential space of the entire biceps with a spatial resolution of 2×2×2 cm^3. The linear relationship between the source space and the measurement space can be expressed as

$$L \cdot X = \Phi. \quad (1)$$

where $\Phi=(\Phi_1, \Phi_2, \ldots, \Phi_M)^T$ is the vector of surface EMG measurements, $X=(x_1, x_2, \ldots, x_{3\times N})^T$ is the vector representing the strength of the distributed dipoles in the 3D space of the biceps, L is the lead field matrix. M refers to the number of surface recording electrodes over the skin and N refers to the number of dipole sources in the source space. The weighted minimum-norm (WMN) regularization technique was adopted to solve the inverse problem and can be expressed by the following equation:

$$\min \left(\|\Phi - L \cdot X\|_2^2 + \lambda \|WX\|_2^2\right). \quad (2)$$

where W is a $3N \times 3N$ weighted matrix which accounts for the undesired depth dependence and λ is the regularization parameter which is determined by means of the L-curve method [12].

III. Results

A. MU#3/Time instant #1: the MUAP train was just generated, and the muscle activities mainly exists in the innervation zone

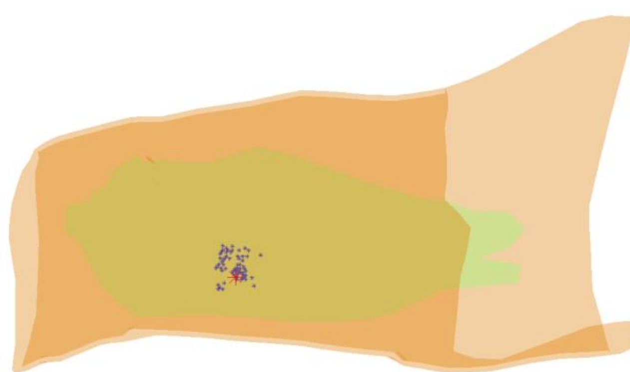


Figure 4. Internal muscle activities reconstructed by using the MAI technique from the 128-channel surface EMG recordings of the MU #3 at the time instant #1 when the 48th surface EMG electrode achieved the maximal value. Blue dots represent the reconstructed internal muscle activities and the red star represents the location of the 48th surface EMG electrode.

The 128-channel surface EMG recordings at the specific time instant #1, when the 48th electrode which is closest to the innervation zone of the MU #3, achieved the maximal value, were selected for the muscle activity imaging calculation. The reconstructed muscle activities in the 3D space of the biceps are visualized in Figure. 4. It can be seen that the reconstructed muscle activities match very well with the innervation zone of the MU #3 (the space under the 48th surface EMG electrode) where the wire electrode was placed.

The depth of the wire electrode inserted into the biceps was characterized from the ultrasound images as 15.3 mm from the skin surface. It was found out that the location of the inserted wire electrode is within the zone described by the muscle activities reconstructed from the surface EMG recordings. These results validated the feasibility of the MAI technique for accurately imaging internal muscle activities from multi-channel surface EMG measurements.

B. MU#3/Time instant#2: the activation zones propagate to the middle between the innervation and termination zones in two opposite directions

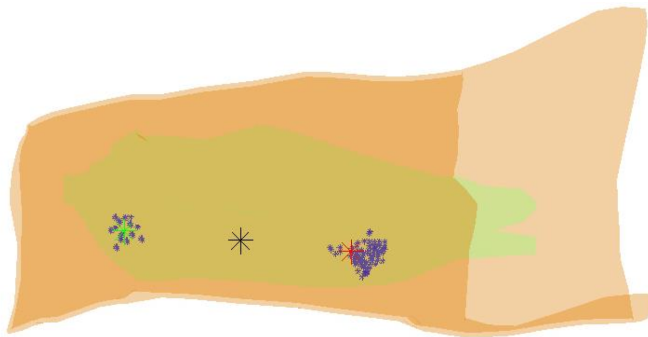


Figure 5. Internal muscle activities reconstructed by using the MAI technique from the 128-channel surface EMG recordings of the MU #3 at the time instant #2 when the 85th surface EMG electrode achieved the maximal value. Blue dots represent the reconstructed internal muscle activities, the red and green stars represent the locations of 85th and 44th surface EMG electrode and the black star represents the innervation zone (48th electrode).

The 128-channel action potentials at another specific time instant #2, when the 85th electrode which was located in the middle of innervation and termination zones of the MU #3 achieved the maximal value, were further tested for muscle activity imaging. The reconstructed muscle activities in the 3D space of the biceps are visualized in Figure. 5. It can be seen that there are two locations of muscle activities that have been reconstructed from the surface EMG recordings for the MU #3 at this time instant. One group of reconstructed muscle activities is underneath of the 85th surface EMG electrode while the other group of reconstructed muscle activities is underneath of the 44th surface EMG electrode. Muscle activities are generated in the innervation zone (the neuromuscular junction) and propagate bi-directionally toward the tendon endings of each fiber where they become extinguished. Therefore, when one group of muscle activities propagates to the location of the 85th electrode along the muscle fibers in one direction, the other group of muscle activities propagates in the opposite direction to arrive at the 44th electrode location. The 85th and 44th electrodes are located the pretty much same distance from the innervation zone (48th electrode) on opposite sides. These results demonstrate that the developed MAI technique can be used to image internal muscle activities accurately. The line between the 85th electrode and the 44th indicate the direction of the muscles associated with the MU #3, while the 48th electrode indicates the location of its innervation zone.

IV. CONCLUSION

The validation results demonstrate the feasibility and validity of the MAI approach in imaging internal muscle activities from multi-channel surface EMG recordings. The MAI approach provides a non-invasive way to study internal muscle activities for identifying neuromuscular diseases.

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