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Temporal Muscle Activation Assessment by Ultrasound Imaging During Flexor Withdrawal Reflex and Voluntary Contraction

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Abstract— **Activating flexor reflexes by electrical stimulation has been used as a mechanism to initiate the swing phase or to enhance it for spinal cord injured patients. However, it is necessary to know their contraction dynamics in order to artificially induce them at the right moment of a walking cycle. This requires understanding the temporal activation pattern of both surface and deep muscles simultaneously. This study aimed at developing a system to measure and analyze the temporal activation of both surface and deep muscles during voluntary contraction and flexor reflexes (also called withdrawal reflexes) using ultrasound imaging. A set of experiments were done to verify the validity of the system, while exploring the temporal pattern of muscle activation during flexor reflexes. As a result, we were able to quantify the surface and deep muscle activity by measuring the muscle thickness, pennation angle and long-axis displacement, from the ultrasound images.**

I. Introduction

The flexor withdrawal reflex is a rapid and automatic defensive response that seeks to pull the injured limb away from potential tissue damaging stimuli. It involves a flexion of the ipsilateral extremity by flexors contraction and inhibition of extensor muscles to withdraw from the stimulus [1]. Activation the flexor reflex by electrical stimulation has been used as a mechanism to initiate the swing phase [2] or to enhance it [3] in the case of spinal cord injured patients. However, the temporal activation order between surface and deep muscles is not well defined. Additionally, the reflexive responses are likely to change due to the weakened inhibition of reflexes, depending on the stage of palsy for paraplegics. Therefore, to study the contraction dynamics of lower limb reflexes is necessary for integrating artificially induced flexor reflexes into a walking function restoration systems or simulation system [4].

Surface Electromyogram (sEMG) is an effective way to assess the surface muscles but presents limitations during electrical stimulation. There are some techniques that can be used to cope with this problem: amplitude threshold to discriminate the EMG from the electrical stimulation signal [5] or comb filter[6][7]. Nevertheless, stimulation artifacts are difficult to eliminate. Also, intramuscular EMG can be used to measure recruitment in deep muscles but is invasive.

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An alternative method to investigate muscle activity is ultrasound imaging. It has been used since 1950 [8] and provides a non-invasive way to investigate the activities of both surface and deep muscles in real time. In most published studies, muscle thickness, pennation angle, and fascicle length have been used to measure muscle activity in voluntary contraction [9], showing that muscle thickness and pennation angle increase and fascicle length decreases during isometric contraction. Also, it has been shown that the largest pennation angle is obtained during maximal contraction [10]. However, the relationship between superficial and deep muscles and the temporal variation of these features in a continuous motion still need to be studied in more detail. Moreover, the temporal aspect of muscle activity induced by reflexes should be precisely investigated.

This study aimed at developing a method to measure the muscle temporal activation of surface and deep muscles of the leg during voluntary contraction and flexor withdrawal reflex using ultrasound imaging and joint angle.

II. Method

Six male subjects (age 23.5±0.8) with no known history of neurological abnormalities or musculoskeletal disorders, participated in the experiments. They were informed about experimental procedures and asked to provide their consent.

Lateral gastrocnemius (LG) and soleus (SOL) muscles were selected as superficial and deep muscles, respectively for the posterior compartment. Tibialis anterior (TA) and tibialis posterior (TP) were chosen as superficial and deep muscles, respectively for the anterior compartment

Muscle contraction was recorded using ultrasound imaging and a motion capture system simultaneously. The Ultrasound imaging device Aplio™XG (Toshiba Medical Systems) was used at 7.2 MHz, and the images were stored at 60 fps. A holder for the ultrasound probe ($60\times80\times50$ mm^3) was developed in order to diminish pressure difference during the measurements, as shown in figure 1. The probe holder pressure was adjusted until muscle fibers were visible and the pennation angle could be measured. The ankle joint angle was measured using a motion capture system (Move-Tr/2D, Library) at 60 fps. Changes in muscle thickness, the pennation angle, and the long-axis displacement were measured from the ultrasound images, as shown in figure 2.

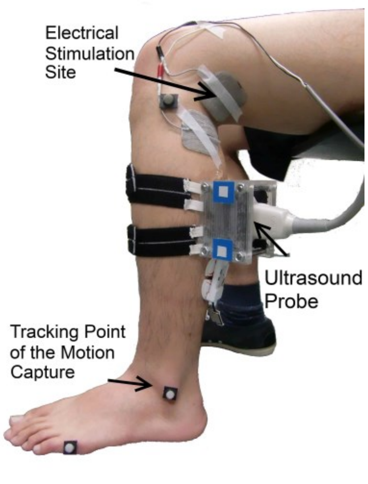

Figure 1. Experiment setup to measure muscle activity during voluntary and flexor reflex activation.

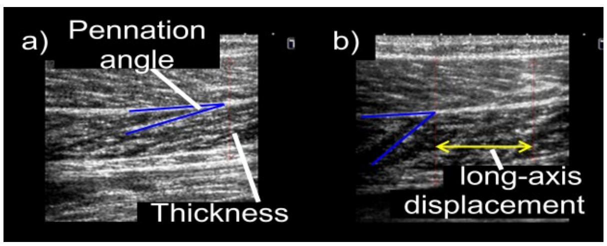

Figure 2. Ultrasound Imaging: a) Resting state, b) Maximum contraction of the lateral head of gastrocnemius (LG). Muscle thickness, pennation angle, and long axis displacement were measured with respect to the resting state.

A. Voluntary contraction Experiment

The subjects were asked to sit on a chair and perform plantar flexion and dorsiflexion for 5 times. The figures 1 and 3 show the setup of the experiment.

B. Flexor withdrawal reflex

Electrodes used to induce flexor reflex by electrical stimulation were placed in the lateral area of the knee [11] as shown in Figure 1. After stimulation of the peroneal nerve, flexion of the hip and knee, and plantar flexion occurred. Tibial nerve stimulation originated a flexion of the hip and knee, and dorsiflexion of the ankle. Measurements were performed five times for each muscle. A pre-modulate electrical stimulation was used in this study with a carrier frequency of 2250 Hz, burst frequency of 30 Hz, and a stimulation duration of 130 ms [12]. The voltage was adjusted for each subject according to their maximum pain tolerance. A square electrode of area 25 cm^2 was employed.

III. RESULTS

A. Relationship between long-axis displacement and joint angle

Figure 4 shows the change of long-axis displacement in LG muscle and joint angle in voluntary contraction. The long-axis displacement and the joint angle had a similar waveform. The average correlation coefficient was (94.0±3.0)% between all subjects.

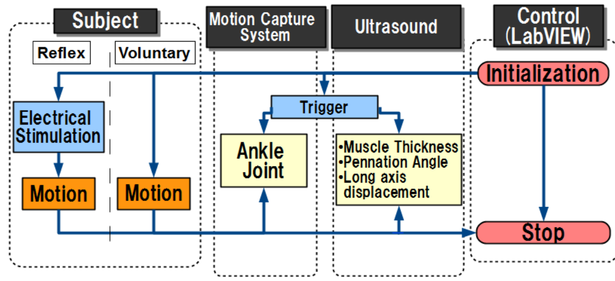

Figure 3. General diagram of the experiment.

B. Relationship between pennation angle, muscle thickness and long-axis displacement during voluntary movement

Figure 5 shows the temporal activation during voluntary contraction and flexor reflex for one representative subject performing a plantar flexion and dorsiflexion of the posterior (LG and the SOL) and anterior muscles (TA, TP), respectively. The temporal activation was evaluated using muscle thickness, pennation angle, and long-axis displacement measured from the ultrasound images. The deep muscle and the surface muscle were then compared using the root mean square error average (RMSE) for all subjects. The resulting RMSE average value between all the subjects was (12.7±4.3)% in muscle thickness, (14.1±2.4)% in pennation angle, and (4.0±3.3)% in long-axis displacement for plantar flexion. It can be noticed that RMSE in muscle thickness and pennation angle were considerable higher than the one of the long-axis displacement.

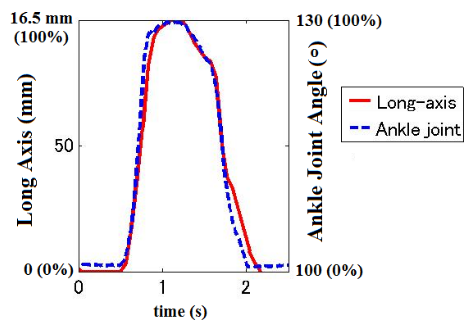

Figure 4. Relationship between long-axis displacement and joint angle during voluntary contraction for one subject. 0% represents the resting state, 100% is maximum contraction. The average correlation coefficient is 0.94

C. Relationship between pennation angle, muscle thickness and long-axis displacement during flexor withdrawal reflex.

Figure 6 shows the temporal activation in reflex contraction for one representative subject performing a plantar flexion and dorsiflexion of the posterior (LG and the SOL) and anterior muscles (TA, TP), respectively. The temporal activation was evaluated using muscle thickness, pennation angle, and long-axis displacement.

D. Voluntary contraction and flexor withdrawal reflex in antagonist and agonist muscles groups

Figure 7 shows the temporal activation of the four muscles for dorsiflexion movement induced by the flexor reflex. Table I summarizes the muscle temporal activation between deep and surface muscles of the posterior and anterior compartment of the plantar flexion and dorsiflexion movements under voluntary and reflex contraction. The muscles in the posterior compartment present an opposite activation order between voluntary and reflex contraction. In the other hand, anterior compartment has the same behavior between voluntary and reflex contraction.

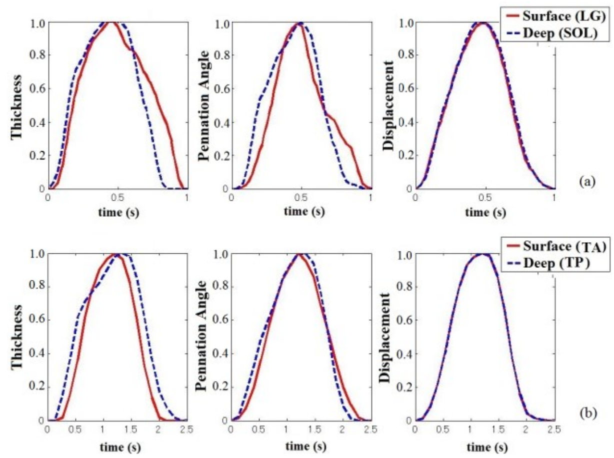

Figure 5. Temporal activation of the agonist muscles performing voluntary tasks: (a) plantar flexion and (b) dorsiflexion, evaluated by the normalized muscle thickness, pennation, angle and long-axis displacement for representative data of one subject.

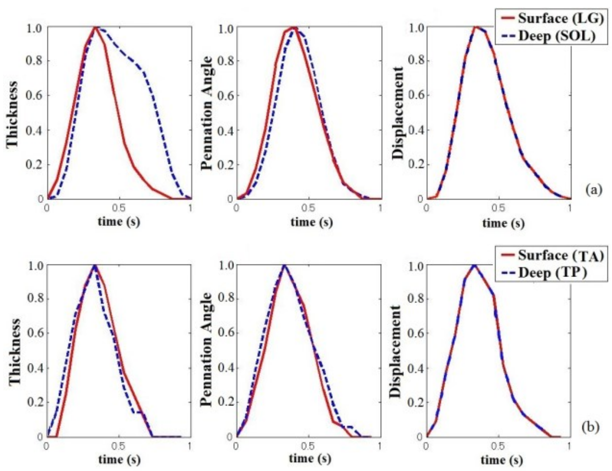

Figure 6. Temporal activation of the agonist muscles during flexor reflex resulting in (a) plantar flexion and (b) dorsiflexion movement, evaluated by the normalized muscle thickness, pennation, angle and long-axis displacement for representative data of one subject.

TABLE I. FIRST MUSCLE ACTIVATED DURING VOLUNTARY AND FLEXOR REFLEX

Compartment	**Motor Task**	***Voluntary***	***Flexor Reflex***
Anterior	Plantar Flexion	Surface (TA)	Surface (TA)
	Dorsiflexion	Deep (TP)	Deep (TP)
Posterior	Plantar Flexion	Deep (SOL)	Surface (LG)
	Dorsiflexion	Surface (LG)	Deep (SOL)

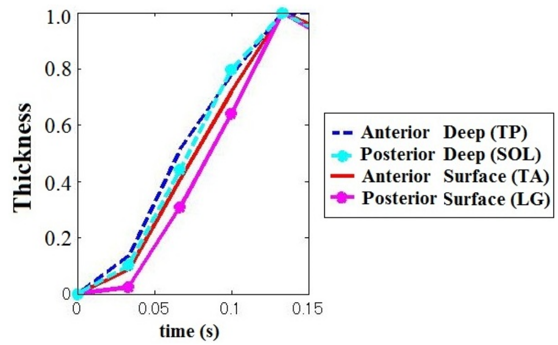

Figure 7. Temporal activation of the posterior and anterior muscles for dorsiflexion during flexor reflex using normalized muscle thickness as measured feature.

IV. DISCUSSION

This study showed a method to obtain muscle activation patterns during voluntary and flexor reflex contraction using ultrasound imaging. In this study, temporal activation pattern between surface and deep muscles of the leg were measured during dorsiflexion and plantar flexion tasks. These tasks were initiated by direct electrical stimulation of the common peroneal and tibial nerve while flexor reflex was activated as well.

Ultrasound imaging has several advantages over surface EMG since the latter has limited applicability to studies of deep muscle recruitment and electrical stimulation muscle activation. Also, geometric factors, such as relative motion of the muscle to the electrodes, and physical factors, such as tissues conductivity, fat thickness, and crosstalk could introduce artifacts to the EMG measurements [13]. Additionally, magnetic resonance imaging (MRI) has been proposed as a method to infer temporal sequence of muscle activation [14] but some contraindication, such as implanted medical devices, claustrophobia, cost, and temporal resolution, have to be taken in consideration. The disadvantage of using ultrasound imaging is that the measured images could be affected by probe placement through different subjects and motions [15]. However, as a result of using the probe holder in this paper, the variation of the angle of incidence, pressure, and muscle thickness were diminished. Additionally, the resolution of the ultrasound used in this study (60 Hz) should be improved to capture reflexes occurring within 30 ms.

From the results, we observed that is possible to measure the ankle joint angle from ultrasound measurement (figure 4) because of the high correlation between long displacement axis and joint angle. Also, the changes between surface muscles and deep muscles of muscle thickness, pennation angle, and long-axis displacement showed a similar tendency under the two motor tasks, as presented in figure 5 and 6. Nevertheless, the duration time from the onset to the maximum contraction is slightly different between surface and deep muscles in the two figures. The muscle thickness and pennation angle indicate that the deep muscle reaches about 80% strength of contraction earlier than the surface muscle in voluntary contraction. However, the time required to reach 100% strength of contraction is the same between the surface and the deep muscles. On the other hand, the long-axis displacement feature showed that the contraction is almost the same between the surface and the deep muscles, as indicated in figure 5 and 6. Further analysis is necessary to determine under which conditions deep muscle dynamics could be predicted from the measurement of surface muscles.

For the anterior compartment, surface muscle (TA) was activated first during plantar flexion and deep muscle (TP) was activated first during dorsiflexion, as shown in table I. For the posterior compartment, an opposite activation pattern between voluntary and flexor reflex was observed (table I). However, the activations patterns are influenced by the speed and motor task. As shown in [16], LG and SOL can be controlled separately under some specific motions and during reflexes [15].

Finally, the temporal activation of the four muscles under dorsiflexion motion resulted in a initial activation of the deep muscles before the surface muscles. Although, the results obtained are preliminary, they suggest a mechanism of activation pattern under a specific task.

V. Conclusion

In order to investigate the possibility of using ultrasound images as a tool of quantitative analysis for muscle activity, this study focused on exploring different features obtained from ultrasound imaging. We were able to quantify the surface and deep muscles activity by measuring the muscle thickness, pennation angle and long-axis displacement under dorsiflexion and plantar flexion movement. In a future study, it is necessary to measure the muscles that are only activated during flexor reflex to elucidate the mechanism of muscle activity and patterns that still are not clear.

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