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Technical note

# Force estimation in fatigue condition using a muscle-twitch model during isometric finger contraction

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ABSTRACT

We propose a force estimation method in fatigue condition using a muscle-twitch model and surface electromyography (sEMG). The twitch model, which is an estimate of force by a single spike, was obtained from sEMG features and measured forces. Nine healthy subjects performed isometric index finger abduction until exhaustion for a series of dynamic contractions (0–20% MVC) to characterize the twitch model and static contractions (50% MVC) to induce muscle fatigue. Muscle fatigue was identified based on the changes of twitch model; the twitch peak decreased and the contraction time increased as muscle fatigue developed. Force estimation performance in non-fatigue and fatigue conditions was evaluated and its results were compared with that of a conventional method using the mean absolute value (MAV). In non-fatigue conditions, the performance of the proposed method ($0.90 \pm 0.05$) and the MAV method ($0.88 \pm 0.06$) were comparable. In fatigue conditions, the performance was significantly improved for the proposed method ($0.87 \pm 0.05$) compared with the MAV ($0.78 \pm 0.09$).



## 1. Introduction

Surface electromyography (sEMG) is the science of recording and interpreting the electrical activity of the muscle fibers active during contraction [1]. Such signals have been widely used to estimate muscle force because they can be measured noninvasively and simply. Force estimation of human muscles with sEMG has been widely studied for the fingers [2], wrist [3], and elbow [4].

In most previous studies, however, the effect of muscle fatigue was not taken into consideration for force estimation. Muscle fatigue can be defined as the changes that occur in areas of the body as a result of sustained or repeated contractions of the muscles. The relationship between the amplitude of sEMG and the muscle force does not remain constant after the onset of muscle fatigue [5]. The manifestation of fatigue has been studied under limited conditions, such as isometric contraction or dynamic contraction with a constant force level (for details refer to [5–8]).

Contessa and De Luca [9,10] reported a force generation model to simulate a neural control of muscle force in fatigue condition. The force generation model consists of an electrical part that is modeled using the firing rate and the number of active motor units and a mechanical part that is modeled using the twitch force. After a single action potential innervates a motor unit (MU), which is composed of a motor neuron and the muscle fibers it innervates, a twitch force is generated [1]. As fatigue progresses, the amplitude of the twitch force decreases and then the input excitation increases to maintain a certain target force. In our previous study [11], we modified the simulation model to experimentally estimate a finger force in non-fatigue conditions using the extracted spikes from sEMG and the muscle-twitch model. The modified twitch model is suitable to use in fatigue condition because the properties of the twitch model can be varied depending on the level of muscle fatigue.

In order to obtain a twitch force, previous studies used an electrical stimulation method using an intramuscular needle or an electrode on the skin [12,13]. The changes in twitch force (i.e., twitch peak and contraction time) have been used for indicators of fatigue. However, these techniques are inconvenient procedures because the stimulation process requires the investigation of the twitch force by electrical stimulation.

In this paper, we assess muscle fatigue using an estimated muscle-twitch model and validate its force estimation performance in fatigue conditions. The proposed method uses a different approach to obtain the muscle-twitch model using sEMG compared with previously reported studies using electrical stimulation.

## 2. Materials and methods

### 2.1. Experimental setup and data collection

The experimental setup is illustrated in Fig. 1(a). A force sensor (651AL, Ktoyo, Korea) was used to measure the isometric ab-

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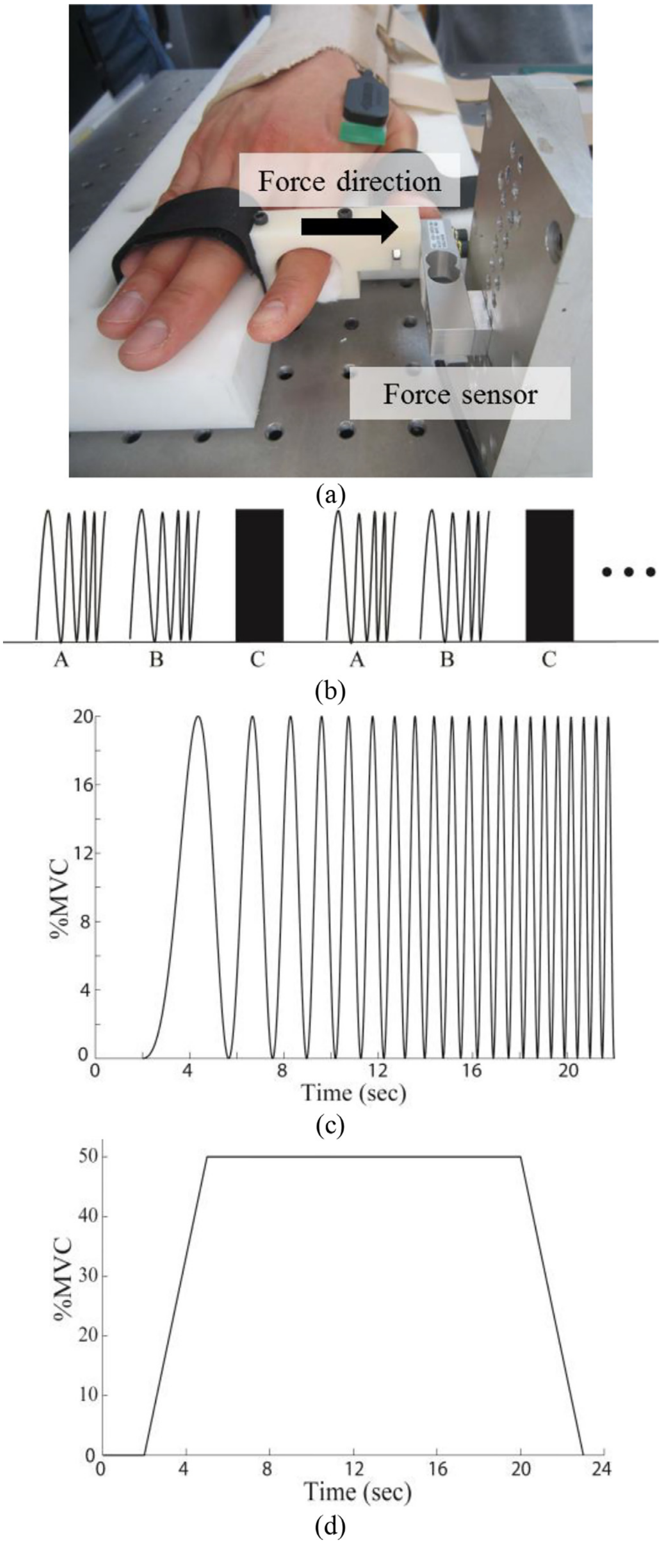


**Fig. 1.** Experimental setup and protocol. (a) A single bipolar electrode was placed on the first dorsal interosseous (FDI) muscle. (b) Sequence of A, B, and C, (c) linear chirp signal with the instantaneous frequency varies linearly with time (0.2 Hz–2 Hz) for A and B, and (d) trapezoidal signal to induce fatigue.

duction force of the index finger. The sEMG of the FDI muscle, which is responsible for the flexion and abduction movement at the metacarpophalangeal (MCP) joint, was recorded using a bipolar sensor (DE-2.1 sensor; Delsys Inc., USA). The FDI muscle was selected because it is composed of a small number of MUs (∼120) that have similar mechanical properties [14]. The position of the electrodes was chosen to be on the belly of the FDI muscle. The instructor found the optimal location where the highest amplitude of sEMG was measured, while a subject generated the abduction force. Before attaching the electrodes parallel to the direction of the index finger, the skin was cleaned with alcohol. The force signal was sampled at 1 kHz and was low-pass filtered with a corner frequency of 20 Hz. The sEMG signal was sampled at 1 kHz and was band pass filtered with a frequency range between 20 and 400 Hz [15].

### 2.2. Experimental procedure

Nine volunteers (right-handed, seven male and two female, 25.0 ± 2.5 years) participated in the experiment. The protocol (KH2010-25) was approved by the Institutional Review Board of the Korea Advanced Institute of Science and Technology.

The subjects were asked to sit comfortably on a chair and to relax their upper limbs. The right index finger was positioned in a custom-fit ring fixed to a force sensor. Other fingers and the forearm were fastened to the table using Velcro straps. The measured force and the target force were displayed on the monitor simultaneously. The subjects performed three maximal voluntary contraction (MVC) trials prior to the main experiments.

After measuring the MVC, the subjects repeated three experimental sessions (one set) until exhaustion, as depicted in Fig. 1(b). In sessions A and B, the subjects were asked to follow a chirp signal; the force linearly varied from 0% to 20% MVC and the frequency linearly varied from 0 Hz to 2 Hz. A total of 21 contractions were performed within each 20 sec interval. To reduce the effects of muscle fatigue during sessions A and B, the contraction level (20% MVC) was selected [16]. In session C, the subjects were instructed to maintain a contraction force of 50% MVC for 14 s (static force) to induce muscle fatigue because most MUs are recruited starting from 50% MVC [9]. When the subjects remained below 50% MVC for 3 s, the experiment was finished. No rest time was provided between sessions.

### 2.3. Force generation model

Contessa and De Luca developed a force generation model using MU firing behavior and a mechanical muscle behavior during simulated isometric contraction [10]. We modified the force generation model to estimate joint force using sEMG as shown in Fig. 2. The spikes are replaced with sEMG features and the same twitch forces are applied to all MUs. The force level is determined by how many MUs are recruited, how fast the MUs are excited, and the properties of twitch force. Here, we assumed that the magnitude and rates of spikes extracted in the sEMG could be used as indicators to estimate how many and how fast MUs are recruited.

The proposed method is described by

$$F_{tot}(t) = x(t) * T(t), \tag{1}$$

where $F_{tot}(t)$, $x(t)$, and $T(t)$ are the joint force, the spike trains extracted from sEMG, and the twitch model, respectively. For the twitch model, the time dependent properties were characterized using the extracted spikes and the measured force.

### 2.4. Spike extraction in sEMG

When two MUAPs occurred within close proximity, they produced a signal with a greater spike; this spike resembled a larger MUAP. The greater the number of MUs recruited in generating the force, the larger the spike of the summed MUAPs appears. The spikes, $x(t)$, in (3) were found using the following Eq. (4), which was used to extract the morphological features of the spikes:

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