



# Medial gastrocnemius is a key muscle for involuntary alternate muscle activity of plantar flexor synergists

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## HIGHLIGHTS

- Alternate muscle activity was associated with physiological tremor of ankle angular acceleration.
- Activity of medial gastrocnemius muscle was accompanied by physiological tremor.
- Medial gastrocnemius reduces redundant activities of synergists.

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## ABSTRACT

Redundant and/or complicated muscle activations between synergist muscles have been demonstrated during low-level sustained contractions. Identification of a key muscle for this phenomenon allows for the simplification of motor control during prolonged contraction. In this study, we have identified a key muscle for involuntary alternate muscle activity of plantar flexor muscles based on a physiological tremor sequence that was recorded over 120 min. Two epochs where the muscle activity of medial gastrocnemius abruptly increased with decrease in other synergists (*case ON*) and vice versa (*case OFF*) were analyzed. Our results indicated that involuntary alternate muscle activity was associated with changes in physiological tremor of ankle angular acceleration when the muscle activity of medial gastrocnemius decreased in *case OFF*. In particular, the activity of the medial gastrocnemius muscle, but not the activity of other synergists, was accompanied by physiological tremor, demonstrating that the medial gastrocnemius is a key muscle for involuntary alternate muscle activity in plantar flexor synergists. In addition, weaker correlations between muscle activities and physiological tremor were found in *case ON* than *case OFF*. We suggest that, if the central nervous system can employ this unique muscle strategy, redundant and/or complicated neuromuscular activities will be reduced because of the existence of the key muscle.

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## 1. Introduction

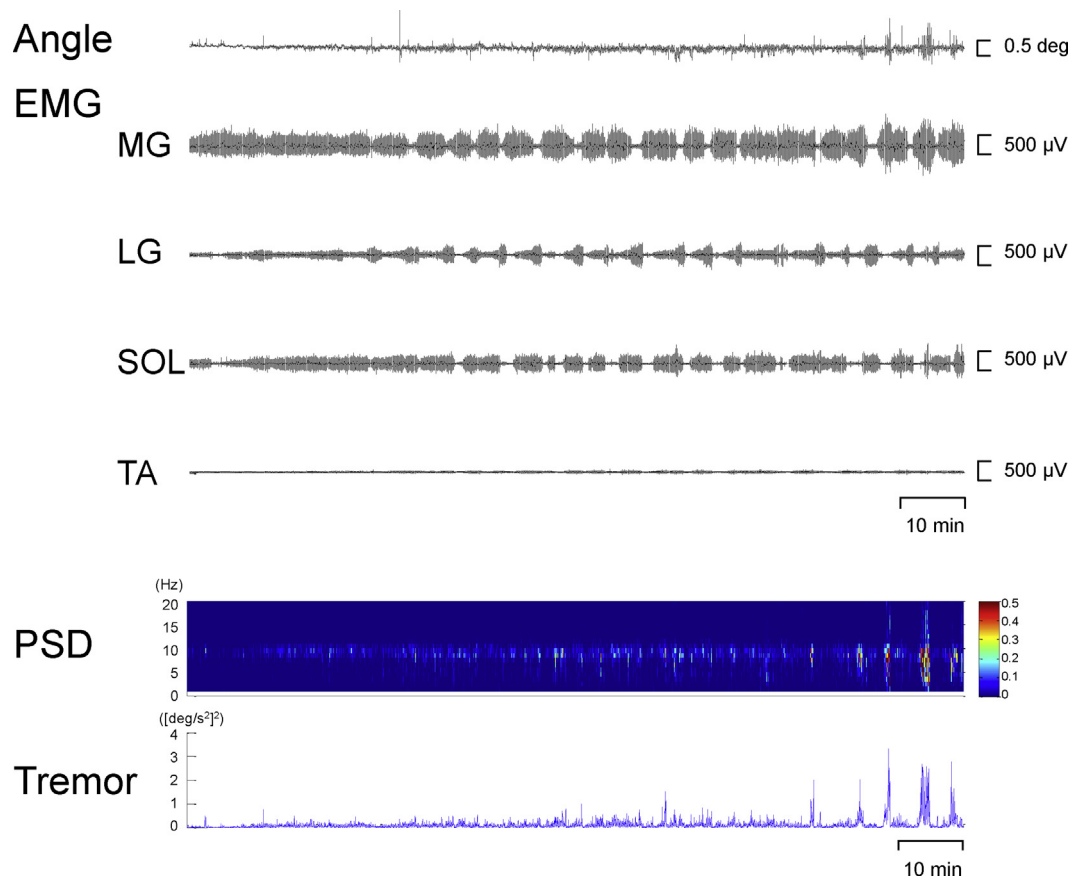
In low-level, prolonged contraction ( $\leq 10\%$  of maximal voluntary contraction; MVC), the synergist muscles are not continuously activated, but rather are activated in an alternating pattern of activity and silence. Unique activation within synergistic muscles has been observed in synergist muscle groups, including knee extensor [1,11,14–16] and plantar flexor [19,22,23] muscles. This unique strategy of synergistic muscles has been referred to as “*alternate muscle activity*” [12,15]. However, the neural mechanism of alternate muscle activity has not been elucidated.

Our studies using knee extensor muscles have reported that alternate muscle activity occurred in the rectus femoris muscle

and either vastus lateralis or vastus medialis muscles, suggesting that the emergence of alternate muscle activity in knee extensor synergists is related to the neural properties of the rectus femoris muscle [12,15]. Thus, this muscle can be defined as a key muscle for simplifying alternate muscle activity including complex neural circuit among synergists [11,12]. However, it is very difficult to reveal the aspect of the alternate muscle activity in plantar flexor muscles because alternations of plantar flexors are more complicated than those of knee extensors. In knee extensor muscles, the alternate muscle activity is found only between rectus femoris and both vasti-muscles [14,15]. On the other hand, there are numerous combinations of alternate muscle activity among individual muscles composing plantar flexor synergists [23], and it seems that alternate muscle activity of plantar flexors emerges without regularity [22,23]. In addition, overlapped activities between the muscles are observed in the plantar flexors [22] not in the knee extensors [14,15] during alternate muscle activity. This overlap complicates the characteristics of alternate muscle activity of plantar flexor synergists. Therefore, the key muscle in the involuntary alternate muscle activity of plantar flexor synergists remains unclear.

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**Fig. 1.** Representative data demonstrating involuntary activation during prolonged plantar flexion for 120 min. Ankle angle, surface electromyogram (EMG) of medial gastrocnemius (MG), lateral gastrocnemius (LG), soleus (SOL), and tibialis anterior (TA) muscles, results of the time-frequency analysis of ankle angular acceleration, and the tremor component sequence of ankle angular acceleration are shown. Time-frequency analysis of ankle angular acceleration for 1 s segments is represented as a color map. Blue and red indicate lower and higher power spectrum density, respectively. Tremor component was calculated by integrating 8–12 Hz of angular acceleration.

In knee extensor synergists, alternate muscle activity is accompanied by physiological tremor, with cyclic force fluctuations of 8–12 Hz, and this parallel activity is related to the rhythmical activity of rectus femoris muscle, which is a key muscle for this activity [14]. By investigating high-frequency motor variability of these fluctuations, the physiological tremor that accompanies alternate muscle activity could be quantified, allowing the identification of a key muscle for alternate muscle activity. Hence, the present study identified the key muscle for the complicated alternate muscle activity of plantar flexor muscle based on the observed physiological tremor. The findings of this study indicate that the existence of this specific muscle reduces redundant and/or complicated neural commands from the central nervous system (CNS) during prolonged contraction.

## 2. Methods

Twelve healthy male subjects (aged  $23 \pm 1.4$  years) voluntarily participated in this study. The subjects provided written informed consent regarding participation in the study after receiving a detailed explanation of the purpose, potential benefits, and risks associated with participation. All procedures used in this study were in accordance with the *Declaration of Helsinki* and were approved by the Committee for Human Experimentation at the Graduate School of Human and Environmental Studies, Kyoto University.

Each subject was seated on a chair designed to secure his leg in full extension. With the knee joint in full extension, the subject's foot was placed on a footplate at  $110^\circ$  of plantar flexion

( $90^\circ$  equaling the right angle of the ankle). The subject maintained this ankle angle at  $110^\circ$  for 120 min while supporting a load hung from the footplate. The suspended load created horizontal tension pulled horizontally in the direction of dorsiflexion, and the load corresponded to 10% of subjects' isometric maximal voluntary contraction at  $110^\circ$  of the ankle joint [22,23]. To maintain the ankle angle, the displacement of the ankle angle was measured from a distance with a charge-coupled device laser displacement sensor (LK-2500, Keyence, Osaka, Japan) with a spatial resolution of  $10 \mu\text{m}$  [10]. Laser displacement sensor was positioned 35 cm apart to the plastic plate attached to a footplate. Present study employed the position-holding task as prolonged contraction because greater fluctuations in motor output and more frequent bursting EMG activity during position-holding task than during isometric force task have been reported [7,8]. Surface electromyogram (EMGs) from skin surface over the medial head of gastrocnemius (MG), lateral head of gastrocnemius (LG), soleus (SOL), and tibialis anterior (TA) muscles were recorded with Ag-AgCl electrodes with a diameter of 5 mm and an interelectrode distance of 20 mm. The electrodes were connected to a preamplifier and a differential amplifier with a bandwidth of 5 Hz to 1 kHz (MEG-6116M, Nihon-kohden, Tokyo, Japan). All signals were sampled at a rate of 1 kHz by a 16-bit analog-to-digital converter (PowerLab/16SP, ADInstrument, Sydney, Australia) and were stored on the hard drive of a personal computer for later analyses.

In the sustained contraction task, alternate EMG activity [11,14–16] was observed among plantar flexor synergists in all subjects. In particular, the reciprocal EMG activity between MG and either LG or SOL could be found throughout the task (Fig. 1).

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