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The relationship between changes in joint kinematics parameters and mechanomyographic signals during non-isometric contraction in human skeletal muscle

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The present study determines the effects of summation of contraction on joint kinematics in human ankle and mechanomyography (MMG) signals during non-isometric contraction. The excursion and angular velocity of dorsiflexion and eversion were measured during several summation profiles during non-isometric contractions. The joint kinematics parameters and MMG responses to 1–8 pulses at a constant interval of 10 ms were recorded to investigate the effects of different numbers of stimuli. In an examination of two-pulse trains with different inter-pulse intervals, the joint kinematics parameters and MMG responses to inter-pulse intervals of 10–100 ms were recorded from the tibialis anterior muscle. The main finding was that facilitating effects of subsequent stimulation were limited to angular velocity of eversion during the contribution of a second stimulus, suggesting that facilitating effects of second stimulus reflect angular velocity but not joint angle excursion. A comparison with MMG signals clarified that MMG signals poorly correlate with changes in the joint kinematics parameters (excursion and angular velocity) when the inter-pulse intervals or numbers of stimuli are increased. These findings will provide useful information for assessing the muscle contractile properties with evoked MMG signals during non-isometric contraction.

Key words: *functional electrical stimulation, twitch, tibialis anterior muscle, MMG, summation of contraction*

1. Introduction

The mechanomyographic (MMG) responses of contracting muscles reflect the ‘‘mechanical counterpart’’ of motor unit activity as measured by electromyography [1]. Others have reported that changes in the evoked MMG amplitude reflect changes in peak twitch torque [2]–[4]. These previous studies suggested that the MMG amplitude during evoked contraction could be used to assess changes in muscle function. Moreover, the MMG response reflects muscle mechanical properties not only during isometric, but also non-isometric contraction [5], [6]. However, systematic studies in the ability of evoked MMG signal in non-isometric contraction to detect the muscle contractile properties have not been conducted. An advantage of the technique of electrical stimulation is that it is possible to obtain measurements of the muscle contractile properties without the influence of the voluntary neural drive. Thus, to clarify the usefulness of evoked MMG, it is necessary to examine the MMG response evoked by several stimulation conditions in the non-isometric contractions.

It is well known that, in the non-isometric contractions, increases in joint angular velocity and joint angle excursion are related to not only increased motor unit recruitment and an increased firing rate, but also the summation of contraction. In the isometric contractions, a dramatic increase in the peak force is observed during the early phase of tetanic summation. For example, the force response evoked by two closely spaced stimuli is larger than that induced by two or three single twitch responses [7]–[9]. In this early phase of tetanic

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summation, structural changes in the muscle thin filaments [10] and tendinous tissue [9] were observed between the first and second stimulation during the application of two closely spaced stimuli. These results suggest that structural changes in the muscle–tendon component between the first and second stimuli generate muscle surface vibrations. However, the previous study suggested that evoked MMG did not detect this surface vibration in isometric contractions during the early phase of tetanic summation [11]. This study hypothesized that if effects of summation of contraction on the mechanical muscle changes are the same as the isometric contraction in the non-isometric contraction, evoked MMG signal during non-isometric contraction poorly correlates with changes in joint kinematics (e.g., excursion and angular velocity).

Although several previous studies have clarified force summation profiles during isometric contraction in human skeletal muscle, such profiles have never been evaluated during non-isometric contraction. Few studies have investigated the effects of several stimulation conditions on the changes in human joint angle [12]–[14]. However, human joint kinematics during early phase of tetanic summation are unclear. Non-isometric contractions comprise an important component of normal movement. Moreover, electrical stimulation (functional electrical stimulation: FES) is used to produce purposeful joint angle changes in patients with paralysis. The human joint kinematics during early phase of tetanic summation is related to onset of joint movement, and that control is an important problem to FES. Therefore, clarifying the human joint kinematics during early phase of tetanic summation will add up to basic understanding of muscle physiology and will be useful for the clinical application of FES.

The present study investigates changes in MMG response and human joint kinematics produced under several summation conditions because summation profiles are affected by an inter-pulse interval of two-pulse trains as well as the number of stimuli. Therefore, the study aimed to determine the MMG response, human joint kinematics, and its relationship during an early phase of tetanic summation in non-isometric contractions.

2. Materials and methods

2.1. Subjects

Eight healthy males (age 27 ± 2.9 years; height 173 ± 9.1 cm; weight 73 ± 5.5 kg; means ± SD) volunteered for this study. All of them received a full explanation of the study purpose based on descriptions approved by the Ethics Committee of Osaka University of Health and Sport Sciences. All participants provided written, informed consent before participating.

2.2. Experimental setup and signal detection

The participants sat with their arms folded in front of their chests in custom-built chairs with the hip flexed to 90°, the knee joint at 0° (that is, with a straight knee) and a free, relaxed ankle joint. A padded belt was strapped to the chair to support and maintain the position of the leg during tests. All of the participants performed a few voluntary contractions of their dorsiflexor muscles as a warm-up before testing.

Angle changes during dorsiflexion and eversion in the right ankle were determined using a biaxial electrical goniometer (SG110/A, Biometrics, UK). The MMG signal was detected using a 9 mm^2 uniaxial accelerometer, with a thickness of 4.5 mm and a mass of 0.75 g (sensitivity, 500 mV/g (g = 9.8 m/s^2); MP110-10-101, Medisens INS, Japan). The MMG device was secured with double-sided adhesive tape over the tibialis anterior muscle (TA). The MMG signal was amplified and filtered using an AC amplifier with a bandwidth of 0.1–1 kHz. The goniometer position and MMG signals were automatically recorded at a sampling rate of 4 kHz via an analogue to digital converter (PowerLab 8sp, ADInstruments, Australia), before data analysis using software (Chart v5.4.2, ADInstruments).

2.3. Electrical stimulation and experimental procedure

The excursion of ankle angle and MMG signals produced by a single stimulus, two-, three-, four-, seven- and eight-pulse trains delivered to the common peroneal nerve at a constant inter-pulse interval of 10 ms (100 Hz) were recorded to determine the effects of different numbers of stimuli. To examine the effects of two-pulse trains at different inter-pulse intervals, the excursion of ankle angle and MMG signals produced by inter-pulse intervals of 10, 20, 30, 40 50, 80 and 100 ms were recorded.

Stimulation was applied using a 0.5-ms square-wave pulse isolated (SS-104J, Nihon Koden) from a constant voltage stimulator (SEN-3301, Nihon Koden). The cathode (1 cm diameter) and anode (1 cm diameter)

electrodes were placed near the fibular head. The distance between the cathode and anode was 5 cm. Successive stimuli were separated by 1–5 min of rest. The stimulus intensity was 20% greater (supramaximal) than that required to produce a maximal ankle angle change by a single twitch during the resting state. The excursion of the ankle angle and MMG signals were measured three times under each stimulation condition in a random order, and the mean was taken as the representative value for each parameter.

2.4. Analysis of experimental signals

The peak excursion of the ankle angle and the peak velocity of the ankle angle to the dorsiflexion and eversion sides recorded under each stimulation condition were measured. Peak angular velocity was calculated from the first derivatives of the goniometer position signals for each stimulation condition. The amplitude of the first peak of the evoked MMG signal was measured under each stimulation condition [15]. For the excursion of ankle angle and angular velocity, the contribution of the response to the *N*-th stimulation (C2, C3, C4, and C8) was obtained by subtracting the response to the $N - 1$ stimulation from that of the *N* stimulation [8]. For example, the third contribution (C3) of three-pulse trains was obtained by subtracting the response to the two-pulse trains from that to the three-pulse trains.

2.5. Statistical analysis

All data are presented as means ± standard error (SE). Changes in the excursion of ankle angle, angular velocity and MMG amplitude for two-pulse trains with different inter-pulse intervals and the contribution of each stimulus were analyzed by one-way analysis of variance (ANOVA) with repeated measurements. Differences from the response to a single stimulation or C1 were determined using Dunnett's post hoc test. All measured parameters of normalized values at a single pulse with increasing numbers of stimuli (Fig. 8a) and with different inter-pulse intervals (Fig. 8b) were analyzed by ANOVA for each number of stimuli and each inter-pulse intervals. Differences within each measured parameter were determined using Tukey's post hoc test. The significance level was <5%. All the data were statistically analyzed using SPSS software (Statistical Package for the Social Sciences, SPSS for Windows, version 11.0, USA).

3. Results

Typical excursions of ankle angle, MMG signals and angular velocity for different numbers of stimuli are shown in Fig. 1. The peak excursion of produced dorsiflexion and eversion sharply increased from sin-

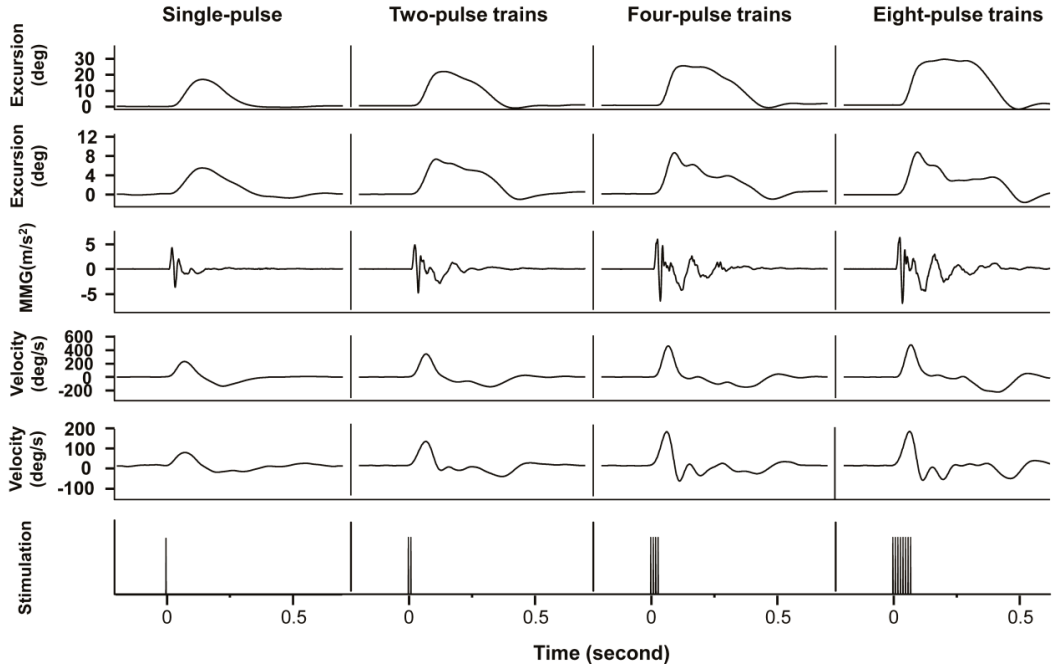

Fig. 1. Excursion of dorsiflexion (top trace), eversion (second trace), MMG signals (third trace), angular velocity of dorsiflexion (fourth trace), eversion (fifth trace), and stimulation (bottom trace) in response to single-, two-, four- and eight-pulse trains at a constant inter-pulse interval of 10 ms in a typical individual

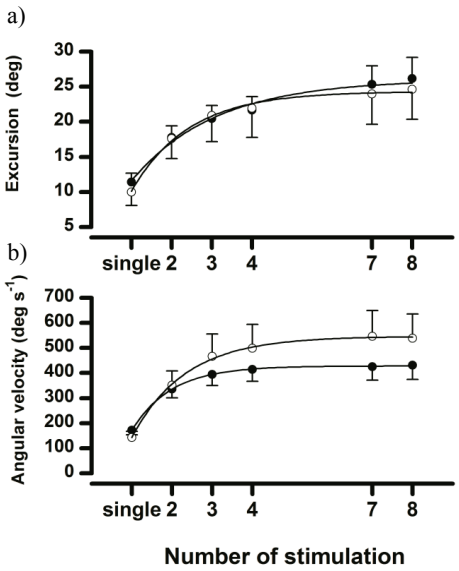

Fig. 2. (a) Changes in excursion of dorsiflexion (●) and eversion (○), and (b) angular velocity of dorsiflexion (●) and eversion (○) produced by different numbers of stimuli. All values are shown as means ± SE of eight individuals. Lines of best fit are shown

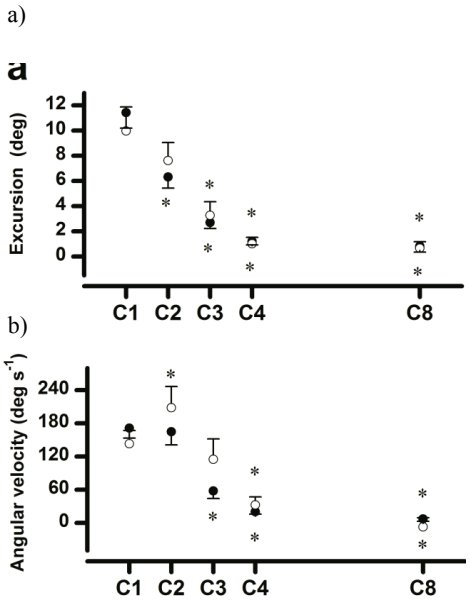

Fig. 3. (a) Changes in excursion of dorsiflexion (●) and eversion (○), and (b) angular velocity of dorsiflexion (●) and eversion (○) in response to a single pulse (C1), and the contributions of the second (C2), third (C3), fourth (C4) and eighth (C8) pulses in two-, three-, four- and eight-pulse trains, respectively. All values are shown as means ± SE for eight individuals. *Significantly different from single pulse at $p < 0.05$

gle pulse to three-pulse trains and the rate of the increase above four-pulse trains was slower (Fig. 2a). The changes in the peak angular velocity of dorsiflexion and eversion for increased numbers of stimuli are shown in Fig. 2b. Like the excursion results, the peak velocity of dorsiflexion and eversion produced sharply increased from single to three pulse trains, and slightly changed above four pulse trains.

The excursion of dorsiflexion and eversion for a single (C1) pulse and the contributions of a second (C2), third (C3), fourth (C4) and eighth pulse (C8) are shown in Fig. 3a. The excursion of dorsiflexion was significantly lower for C2, C3, C4 and C8 than for C1. In the eversion, C3, C4 and C8 were significantly lower than C1. The angular velocity of dorsiflexion and eversion for C1, C2, C3, C4, and C8 is shown in Fig. 3b. The angular velocity of dorsiflexion was significantly lower for C3, C4, and C8 than C1, but C1 and C2 did not significantly differ (Fig. 3b). In contrast, the angular velocity of eversion for C2 was significantly higher than for C1, whereas C4 and C8 in eversion were significantly lower than C1 (Fig. 3b).

Typical ankle angle changes, MMG signals and ankle angle velocity recorded from two-pulse trains with different inter-pulse intervals are shown in Fig. 4. Although the peak excursion of dorsiflexion and eversion was greater for two-pulse trains than for single-pulse at all inter-pulse intervals (Fig. 5a), peak angular velocity was greater in two-pulse trains than in single-pulse at an inter-pulse interval of 10–50 ms (Fig. 5b).

The second contribution (C2) of excursion of dorsiflexion and eversion for two-pulse trains at different inter-pulse intervals is shown in Fig. 6a. The excursion of dorsiflexion and eversion were significantly lower for C2 than for C1 at all inter-pulse intervals (Fig. 6a). In contrast, the angular velocity of eversion was significantly higher for C2 than for C1 at inter-pulse intervals of 10 and 20 ms (Fig. 6b) and significantly lower for C2 than C1 at 80 and 100 ms. During dorsiflexion, the C2 of angular velocity at an inter-pulse interval of 40–100 ms was significantly lower than that of C1, but C1 and C2 did not significantly differ at inter-pulse intervals of 10–30 ms.

The changes in MMG amplitude for increasing numbers of stimuli are shown in Fig. 7a. The produced MMG amplitude sharply increased from single- to three-pulse trains, and did not change above four-pulse trains. The changes in MMG amplitude for two-pulse trains at different inter-pulse intervals are shown in Fig. 7b. Only single-pulse and two-pulse trains at an inter-pulse interval of 10 ms significantly differed.

The changes in all measured parameters of normalized values at a single pulse with increasing numbers of stimuli are shown in Fig. 8a. The angular velocity of eversion was significantly higher at any number of stimuli than all measured parameters. In contrast, MMG amplitude was significantly lower

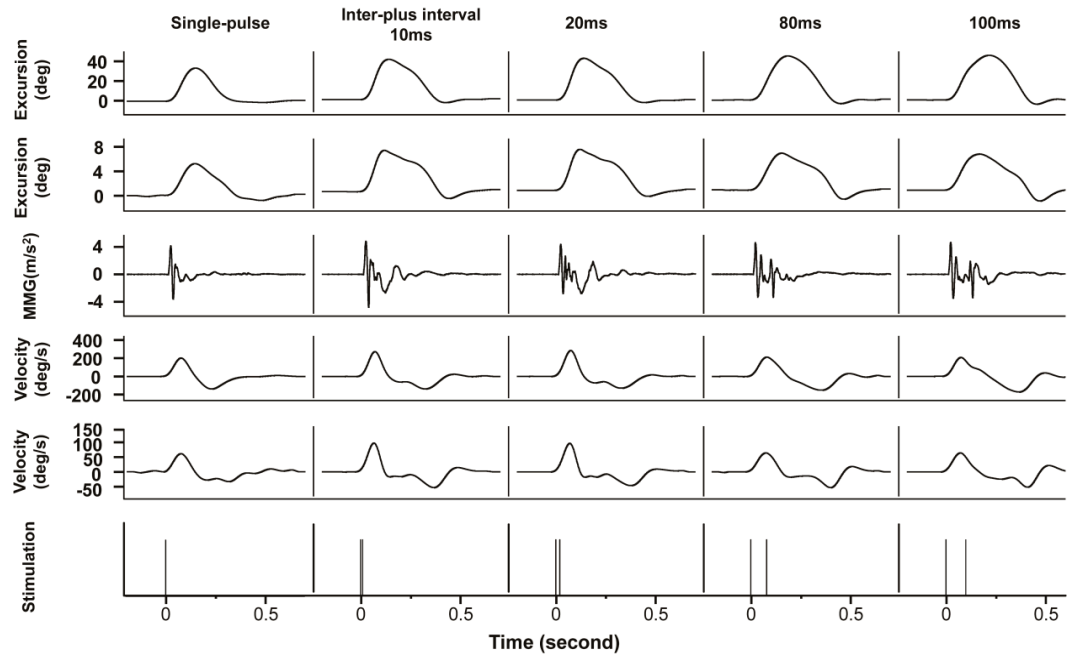

Fig. 4. Excursion of dorsiflexion (top traces), eversion (second trace), MMG signals (third trace), angular velocity of dorsiflexion (fourth trace), eversion (fifth trace), and stimulation (bottom trace) response to single-pulse and two-pulse trains at inter-pulse intervals of 10, 20, 80 and 100 ms in a typical subject. All values are shown as means ± SE of eight subjects. *Significantly different from single pulse at $p < 0.05$

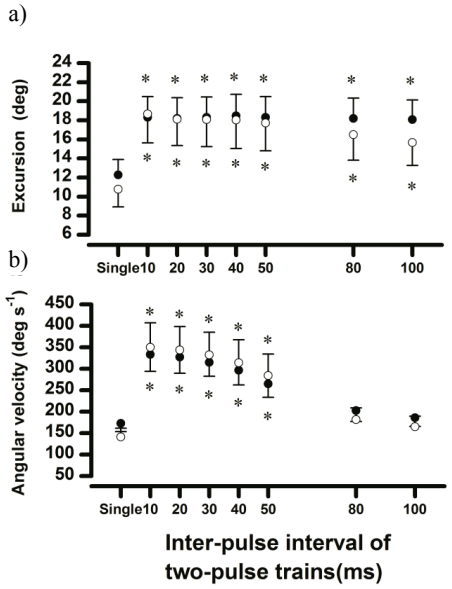

Fig. 5. (a) Changes in excursion of dorsiflexion (●) and eversion (○), and (b) angular velocity of dorsiflexion (●) and eversion (○) in two-pulse trains at different inter-pulse intervals. All values are shown as means ± SE for eight individuals. *Significantly different from single pulse at $p < 0.05$

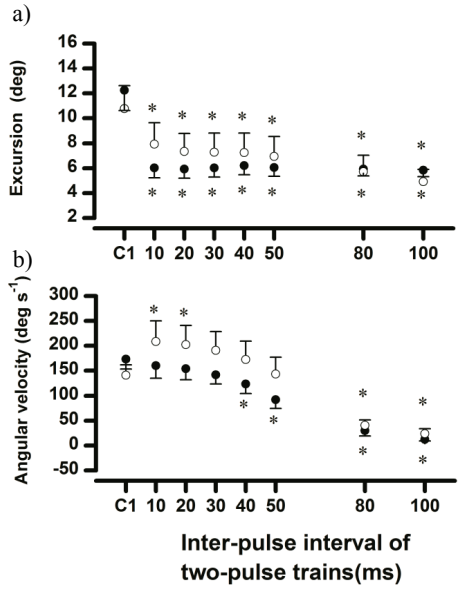

Fig. 6. (a) Changes in excursion of dorsiflexion (●) and eversion (○), and (b) angular velocity of dorsiflexion (●) and eversion (○) in response to single pulse (C1) and contribution of second pulse (C2) in a two-pulse train with different inter-pulse intervals. All values are shown as means ± SE for eight individuals. *Significantly different from single pulse at $p < 0.05$

than the excursion of eversion and angular velocity of dorsiflexion and eversion in the two- to seven-pulse trains. In the eight-pulse trains, MMG amplitude was significantly lower than all measured parameters. The changes in all measured parameters of normalized values at a single pulse at different inter-pulse intervals are shown in Fig. 8b. The angular velocity of eversion was significantly higher than all parameters at an inter-pulse interval of 10–50 ms, but it did not differ and was significantly lower at inter-pulse inter-

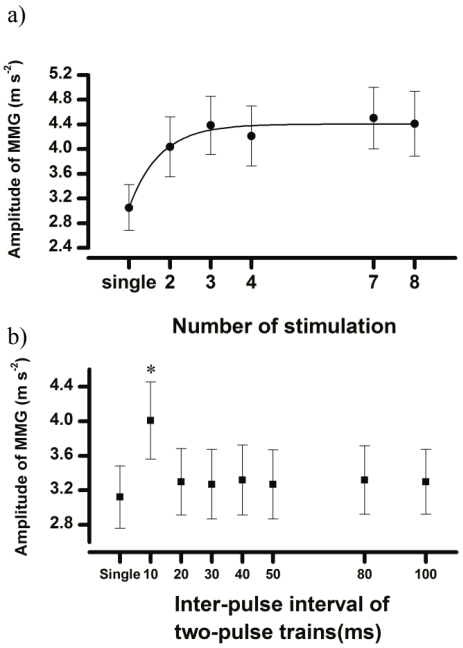

Fig. 7. (a) Changes in MMG amplitude produced by different numbers of stimuli; (b) changes in MMG amplitude in two-pulse trains with different inter-pulse intervals. All values are shown as means ± SE for eight subjects. *Significantly different from single pulse at $p < 0.05$. Lines of best fit are shown

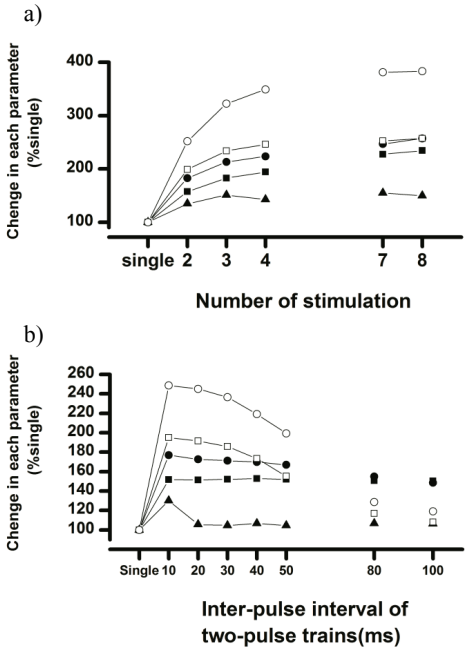

Fig. 8. (a) Changes in exclusion of dorsiflexion (■) and eversion (●), angular velocity of dorsiflexion (○) and eversion (□), and MMG amplitude (▲) of normalized value at single pulse with increasing numbers of stimuli; (b) changes in exclusion of dorsiflexion (■) and eversion (●), angular velocity of dorsiflexion (○) and eversion (□), and MMG amplitude (▲) of normalized value at single pulse in two-pulse trains at different inter-pulse intervals

vals of 80 and 100 ms, respectively. The MMG amplitude was significantly lower than all parameters at 20- to 50-ms inter-pulse intervals. At 10-ms inter-pulse intervals, MMG amplitude was significantly lower than the excursion of eversion and angular velocity of dorsiflexion and eversion. The MMG amplitude and excursion of dorsiflexion and eversion at inter-pulse intervals of 80 and 100 ms significantly differed.

4. Discussion

The present study is the first to analyze several dynamic contraction-induced summation conditions using two-pulse trains at different inter-pulse intervals and different numbers of stimuli. The main finding was that the facilitating effects of subsequent stimulation were limited to angular velocity of eversion during the contribution of a second stimulus (C2). This facilitating effect of C2 occurred at 10–30 ms, but not at over 40-ms inter-pulse intervals. In a comparison with MMG signals, the present study showed that MMG signals poorly correlate with changes in joint kinematics parameters (excursion and angular velocity) when the inter-pulse intervals or numbers of stimuli are increased.

4.1. Effects of different numbers of stimuli on ankle joint kinematics

During isometric contractions, peak torque responses increased with increasing numbers of stimuli. Previous studies found a facilitating effect of second and third stimulation because torque contribution of the second (C2) and third (C3) stimulation was higher than that of the first stimulation (C1) [8], [9]. For non-isometric contractions in this study, unlike the torque response the facilitating effects of the second or third stimulations are generally absent in excursions of dorsiflexion and eversion because C2, C3, C4 and C8 of the joint angle excursion were lower than C1 (Fig. 3a). Ohta et al. [9] reported that a second or third stimulation has no facilitating effect on tendinous tissue elongation in the human TA. Thus, exclusion of the ankle joint might be associated with muscle architectural changes during the early phase of tetanic

summation but not with muscular force output. In contrast, the present study found that a second stimulation facilitates the angular velocity of eversion (Fig. 3b). These findings indicate that facilitating effects of second stimulation reflect angular velocity but not joint angle excursion. This may be expected based on Newton's second law of motion (F = ma). Namely, the changes in angular velocity reflect the changes in muscular force output. However, this facilitating effect occurred during eversion, but not dorsiflexion (Fig. 3b). Electrical stimulation of the common peroneal nerve can produce dorsiflexion and eversion, but ankle eversion interferes with the detection of ankle dorsiflexion [16]. Thus, absence of a facilitating effect of dorsiflexion might be due to eversion interfering with dorsiflexion through common peroneal nerve stimulation.

4.2. Effects of two-pulse trains at different inter-pulse intervals on ankle joint kinematics

An isometric study has shown that a decrease in the inter-pulse interval of two-pulse trains increases evoked peak torque [11], [17]. In the present study, the excursion of dorsiflexion and eversion differed very little among different inter-pulse intervals (Fig. 5a). This result is similar to a change of tendinous tissue elongation of two-pulse trains with different inter-pulse intervals [18]. In contrast, the angular velocity of dorsiflexion and eversion increased with decreasing the inter-pulse interval of two-pulse trains (Fig. 5b). Thus, these results indicate that excursion of the ankle angle is minimally influenced by inter-pulse intervals. However, inter-pulse intervals were determinants of the angular velocity of dorsiflexion and eversion during early phase of tetanic summation.

The results of angular velocity at different inter-pulse intervals (Fig. 5b) were similar to peak torque changes during isometric contraction of two-pulse trains with different inter-pulse intervals [11]. However, regarding the angular velocity for C2, the greater angular velocity for C2 compared to C1 was only observed in eversion at inter-pulse intervals of 10–30 ms but not at over 40 ms inter-pulse intervals (Fig. 6b). The present results differed from changes in torque contribution for C2 because the greater peak torque for C2 compared to C1was observed with inter-pulse interval of 10–100 ms [11]. These results indicated that kinematics of human ankle joint during early phase of tetanic summation differs from torque changes. Therefore, the present study suggests that it is inappropriate to take a torque changes into account to control of initial joint movement using functional electrical stimulation.

4.3. MMG response and dynamic performance

Previous studies have shown that the MMG response reflects muscle mechanical properties during non-isometric contraction [5], [6]. The present study found similar changes between MMG amplitude and joint kinematics parameters at different numbers of stimuli (Figs. 2a, 2b and 7a). However, the magnitude of the rate of MMG change was significantly lower than that of the joint kinematics parameters (Fig. 8a). Moreover, at different inter-pulse intervals of two-pulse trains, the change in MMG amplitude differed from that in joint kinematics parameters (Figs. 7b and 8b). Therefore, the present findings indicate that MMG signals poorly correlate with changes in joint kinematics parameters (excursion and angular velocity) when the inter-pulse intervals or numbers of stimuli are increased. This MMG and joint kinematics parameters relationship during non-isometric contractions is similar to that between MMG and force parameters during isometric contractions at the early phase of tetanic contraction [11]. This poor relationship may be due to the long interval for the peak force by subsequent pulses relative to the time at which MMG peak is achieved [11]. Thus, MMG signals should be carefully analysed when they are used to assess changes in contractile properties of muscle caused by the summation of contraction during isometric and non-isometric contractions.

5. Summary

The present study revealed that facilitating effects of subsequent stimulation reflect angular velocity but not joint angle excursion. Moreover, this facilitating effect of a second stimulation occurred in two-pulse trains of 10–30 ms, but not in over 40 ms inter-pulse intervals. A comparison with MMG signals confirmed that MMG signals poorly correlate with changes in joint kinematics parameters (excursion and angular velocity) when the inter-pulse intervals or numbers of stimuli are increased. These findings provide useful information about how to assess the muscle contractile properties using a MMG during non-isometric

contractions. Furthermore, MMG signals should be carefully analysed when they are used to assess changes in the dynamic contractile properties of muscle caused by the summation of contraction.

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