The effect of neuromuscular electrical stimulation on muscle EMG activity and the initial phase rate of force development during tetanic contractions in the knee extensor muscles of healthy adult males

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ABSTRACT. Objective: Neuromuscular electrical stimulation (NMES) has been noted as an effective pre-contraction for an increase of neural and muscle factors during twitch contractions. However, it is unknown if this intervention is effective for the rate of force development (RFD), which is the ability to increase joint torque strength as quickly as possible, during tetanic contractions. NMES can be safely used by anyone, but, the strength setting of NMES requires attention so as not to cause pain. Therefore, the purpose of this study investigated whether NMES at less painful levels was effective for RFD during tetanic contractions. We also investigated effect activation by analyzing electromyogram (EMG) and RFD for each phase. Methods: Eighteen healthy males were studied. Before and after NMES intervention at 10% or 20% maximal voluntary isometric contraction (MVIC) level (10%NMES, 20%NMES respectively), EMG activity and the initial phase (30-, 50-, 100-, and 200-msec) RFD were measured. Visual analog scale (VAS) was also measured as an indicator of pain during each NMES. Results: 20%NMES increased EMG activity and 30-, 50-, and 100-msec of RFD during MVIC, but could not improve 200 msec of RFD. However, 10%NMES could be failed to increase all phases RFD, but VAS was lower than that of 20% NMES. Conclusion: These results suggest that muscle pre-contraction using 20%NMES could induce moderate pain, but could be an effective intervention to improve RFD via neural factor activity.

Key words: Electromyography (EMG), Healthy subjects, Neuromuscular electrical stimulation (NMES), Pain, Rate of force development (RFD)

It has been recognized that it is essential to improve the rate of force development (RFD) during muscle contraction in various environments1. RFD, which is the ability to increase joint torque strength as quickly as possible12. Notably, the initial phase (30-, 50-, 100-, and 200-msec)—when muscular strength rises—has the most significant importance on the RFD to rapidly reach a given magnitude of muscle force13. RFD has been reported to be more related to sprint time (5 m and 20 m runs) and jumps height in the athlete14. RFD of hip abductor strength also contributes to the stability of one-leg standing in the older adults15. In addition, RFD indicates an association with the activity of daily living scores in older adults16. Therefore, RFD seems to be important to a factor related to both sport-specific and functional daily tasks. RFD is different from the factors involved by phase. The more early phase in the initial phase of RFD has consensus which affected by an increase in a neural factor which the number of motor unit activation and the rates at which motor neurons discharge action potentials17. In addition, it is reported that the later phase in the
initial phase of RFD has also possible to be caused by muscle factor, which the rate of engagement of cross-bridges in the myosin via myosin regulatory light chain phosphorylation. Therefore, the activation of neural and muscle factors is essential to increase RFD.

Muscle pre-contraction increases the number of motor unit activation and the rates at which motor neurons discharge action potentials, as well as myosin regulatory light chain phosphorylation. The magnitude of the potentiation using voluntary contraction is dependent on the strength of the voluntary effort. This phenomenon seems to be related to the fact that the potentiation effect is more susceptible to fast muscle fibers. On the other hand, equipment is required to use MVIC for athletes, and risk management is required to use it for older adults.

Neuromuscular electrical stimulation (NMES) is the muscle contraction method that can be safely used by anyone with only a little equipment. Furthermore, NMES, which is a sufficient neural factor and muscular factor activation method, does not follow the size principle and can activate fast muscle-related motor units with relatively low stimulation intensity. Thus, NMES can activate neural and muscle factors even at low intensity. Some previous studies indicated that NMES at 25-40% maximal voluntary isometric contraction (MVIC) level increases twitch contractions. However, previous studies only measured twitch contractions; thus, it is not clear whether it is effective for RFD during tetanic contractions. In addition, the practical level has not been studied. NMES should be used carefully so as not to cause pain. Our previous study suggested that the levels of pain caused by NMES depend on the intervention intensity, and NMES at 20% of MVIC torque level caused less pain. Therefore, the optimal strength to improve RFD should be investigated at or below NMES of 20% of MVIC torque level so that everyone can tolerate the pain. The purpose of this study was to investigate whether NMES at 10% or 20% of MVIC torque level used as pre-contraction is valid for RFD. We also investigated the factors that influence RFD on each NMES. Additionally, we analyzed factors that affect activation by analyzing electromyogram (EMG) and RFD for each phase.

1. Methods

1.1 Participants

The data for this study were obtained from 18 healthy males (27.3 ± 6.7 years, 175.3 ± 6.8 cm, 69.2 ± 8.5 kg, values are means ± SD) who voluntarily participated from Kobe International University. In this study, subjects with a history of injury to the lumbar region and/or lower limbs were excluded. Subjects were asked to refrain from strenuous exercise for 24 hours before the testing sessions and to not consume caffeinated drinks on the day of testing. This study was approved by the ethics committee on human research at Kobe International University (No. G-2017-060) and was performed in accordance with the Declaration of Helsinki.

1.2 Experimental protocol

The first day, peak torque attained during MVIC of right knee extension measured two times and was adopted as the 100% MVIC value. Peak torque attained during MVIC of knee extension was measured by using an isokinetic dynamometer (CYBEX NORM, Humac, California, USA). Briefly, subjects were placed on the isokinetic dynamometer with a knee joint angle of 45° and performed for 3 seconds for two times. Taking a rest of 10 minutes after measuring 100% MVIC, the current value equivalent to 10%- and 20%- MVIC was measured while progressively increasing the electrical current value of NMES. The next day, the subjects measured RFD and electromyography (EMG) activity of the rectus femoris (RF) muscles during MVIC as the before data. Subjects took a 10 minutes rest to avoid the potentiation effect by MVIC measurement. Taking a rest of 10 minutes after the measurements of the before data, subjects were stimulated by NMES at 10% MVIC torque level (10%NMES) or 20% MVIC torque level (20%NMES) in a randomized for 5 seconds. The intensity of pain induced by NMES were recorded using the visual analog scale (VAS) method immediately after each NMES. After the NMES, subjects again measured RFD and EMG activity during MVIC as the after data. Measurement was performed 1 minute after stimulation because the potentiation effect has possible to be not stable within 1 minute. Subjects performed other stimulation (10% or 20%NMES) on different days. All experiments were conducted in an environmentally controlled room at 25 ± 2°C (Figure 1).

1.3 Visual analog scale measurement

To evaluation of pain intensity during NMES, VAS was compared between 10%NMES and 20%NMES. Subjects were asked to pain intensity immediately after each NMES, and indicated on paper-based VAS. For the VAS, the intensity of pain was rated on a numerical scale from 0 mm to 100 mm (0 mm = no pain, 100 mm = worst pain imaginable).

1.4 Rate of force development measurement

RFD during MVIC of knee extension was measured by using an isokinetic dynamometer. Briefly, subjects were placed on the isokinetic dynamometer with a knee joint angle of 45°. MVIC was maintained for 3 seconds and the subjects rested for 1 minute after the end of the NMES for obtaining the suitable data of RFD. RFD was defined as the slope of the torque-time curve (i.e., Δ torque/Δ time) in time increments of 0-30 (30 msec), 0-50 (50 msec), 0-100 (100 msec), and 0-200 (200 msec) m seconds from the onset of contraction (Figure 2).
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Figure 1. Schematic representation of the experimental protocol
Day 1: measurement of peak torque during MVIC and the electrical current value equivalent to 10%- and 20%- MVIC (10%NMES, 20%NMES respectively). Day 2 or 3: Before and after 10% or 20%NMES intervention, EMG activity and the initial phase (30-, 50-, 100-, and 200-msec) RFD of the right rectus femoris muscle were measured.

Figure 2. Common measurements of Rate of force development (RFD)
Rate of force development (RFD) was defined as the slope of the torque-time curve (i.e., Δtorque/Δtime) in time increments of 0-30 (30 msec RFD), 0-50 (50 msec RFD), 0-100 (100 msec RFD), and 0-200 (200 msec RFD) milliseconds from the onset of contraction

1.5 EMG activity measurement
EMG activity was assessed using an EMG activity sensor (MyoSystem 1400A, Noraxon, Arizona, USA). EMG was recorded using a bipolar electrode (disposable Ag/AgCl, φ34 mm, sensitive area of 13.2 mm², Blue sensor M-00-S, Ambu Sdn. Bhd, Malaysia) on the RF muscle. Briefly, the skin was carefully prepared by shaving, gently abrading, and cleaning with alcohol before electrode placement. Electrodes set with a 1 cm interelectrode distance were attached to the skin over the belly of the muscle, parallel to the predicted direction of RF. The raw EMG signals were filtered using low- and high-pass filters set at 450 and 20 Hz, respectively, and recorded at a sample rate of 1000 Hz. Muscle activity was expressed as the root mean square (RMS) of the EMG amplitude for 1 second in the measurement time.

1.6 Neuromuscular electrical stimulation
Subjects were placed on the isokinetic dynamometer and set at a knee joint angle of 45°. Electrical stimulation was performed using an electrical stimulator (ES-520, Ito Co., Ltd., Tokyo, Japan) and corresponded to 5 seconds of contraction at 50 Hz with a pulse duration of 350 μsec. The electrodes (φ70 mm) were placed on the right RF: one electrode was placed 5 cm upper from the motor point along to RF, and the other was placed on the 5 cm lower from the
motor point along to RF. The intensity of NMES corresponded to 10% or 20% of MVIC.

1.7 Statistical Analysis

Data are reported as means ± SD. All statistical analyses were performed using GraphPad PRISM software version 7.0 (Intuitive Software for Science, San Diego, CA). The normality of the data was determined using the Kolmogorov-Smirnov test. VAS was analyzed by a paired-samples t-test, and RMS of the EMG amplitude and RFD were two-way repeated-measures ANOVA (group; 10% NMES and 20% NMES) × (time; before and after). When a group × time interaction was found, a paired samples t-test was to determine within-group changes from before to after. p-values less than 0.05 were considered statistically significant.

2. Results

2.1 Visual Analogue Scale (VAS) during NMES (Figure 3)

The value of normality of the VAS during 10% NMES and 20% NMES was $p = 0.2$, and $p = 0.2$, respectively. It can be seen from the normality test, each data is normally distributed. VAS during 10% NMES and 20% NMES was 53.2 ± 3.8 mm, 69.1 ± 3.5 mm (mean ± SD), respectively. VAS was lower in 10% NMES than in 20% NMES ($p < 0.05$).

2.2 Root mean square (RMS) of the electromyography (EMG) amplitude during MVIC (Figure 4)

The RMS of the EMG amplitude before 10% NMES was 364.4 ± 167.1 μV, and after 10% NMES was 361.8 ± 167.6 μV. The RMS of the EMG amplitude before 20% NMES was 323.7 ± 137.5 μV, and after 20% NMES was 356.2 ± 147.5 μV. There was significant two-way interaction (time × intensity of stimulation, $p < 0.05$, F = 5.28). In addition, as a result of post hoc testing, the RMS of the EMG amplitude after 20% NMES was increased more than that before 20% NMES.

2.3 Rate of force development (RFD) during MVIC (Figure 5)

Average moment-time curves during MVIC were obtained before and after 10% NMES and 20% NMES. The onset of contraction is denoted by 0 msec. The RFD of before 10% NMES at 30-, 50-, 100-, and 200-msec was 920.1 ± 239.3, 860.1 ± 321.0, 756.6 ± 255.2, and 646.4 ± 251.3 Nm/msec, respectively, and after 10% NMES at 30-, 50-, 100-, 200-msec was 886.5 ± 261.4, 833.3 ± 336.3, 724.4 ± 290.1, and 662.5 ± 232.3 Nm/msec, respectively. The RFD of before 20% NMES at 30-, 50-, 100-, and 200-msec was 917.2 ± 223.1, 831.1 ± 262.1, 708.1 ± 188.9, and 630.4 ± 232.7 Nm/msec, respectively, and after NMES at 30-, 50-, 100-, 200-msec was 1031.1 ± 259.9, 964.7 ± 322.0, 812.8 ± 261.7, and 634.2 ± 163.2 Nm/msec, respectively. There was significant two-way interaction for 30-, 50-, 100-msec RFD (time × intensity of stimulation, $p < 0.05$, F = 6.08, $p < 0.05$, F = 4.29, $p < 0.05$, F = 4.21). In addition, as a result of post hoc testing, 30-, 50-, 100-msec RFD after 20% NMES was increased more than those before 20% NMES.

3. Discussion

In the present study, NMES at 20% of the MVIC torque level for 5 seconds was effective for an increase in 30-, 50-, 100-msec of RFD in healthy subjects. In contrast, NMES at 10% of MVIC torque level intervention failed to increase RFD, but pain was lower than that of NMES at
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Figure 5. Rate of force development (RFD) during MVIC

The value of 30-, 50-, 100-, and 200-msec Rate of force development (RFD) during MVIC at 10%, or 20% torque level using NMES are shown in (A), (B), (C), and (D) respectively. The white bar represents before NMES, and the black bar represents after NMES. The values are means ± SD. * significant difference compared with before group of each intervention, p < 0.05.

NMES at 20% of the MVIC torque level for 5 seconds increased EMG activity and the 30-, 50-, 100-msec of RFD, but could not improve the 200 msec of RFD. It is well known that the magnitude of the EMG activation depends on neural factors, which the number of motor unit activation and the rates at which motor neurons discharge action potentials. Several studies have shown that pre-contraction increase motor unit activity when tested using evoked electromyograms. In addition, muscle pre-contraction activates excitatory postsynaptic potentials (EPSP), which are essential for the depolarization of motor-neuron membranes. Other reports found that NMES at low intensity has some possibility of decreasing the recruitment threshold of the motor unit. Similarly, it is possible that NMES increases the central nervous system (spinal cord and/or cerebral cortex), increasing in motor unit activation. Thus, these results indicated that pre-contraction with NMES at 20% of the MVIC torque level increases neural factors resulting in an increase in EMG activity. Previous studies have reported that the intensity to potentiation of neural factors requires maximal or submaximal voluntary contraction. However, NMES at 20% of the MVIC torque level could not increase the 200 msec of RFD. Maffiuletti et al. indicated that the late phase of the RFD depends more on muscle factors, and the early phase more associated with neural factors. Besides, Other reports indicated that throughout the entire 150 msec of RFD was the relation to increasing EMG activity, which is an index of the neural activity. Considering the results of EMG activity and RFD results, NMES at 20% of the MVIC torque level had possibly to especially increase nerve activity.

On the other hand, NMES at 10% of the MVIC torque level for 5 seconds caused less pain than NMES at 20% of
the MVIC torque level, but not increase EMG activity and all phases of RFD. NMES has been shown to induce pain, depending on the levels of electrical current\(^7\). The strength of electrical current relates to muscle contraction strength\(^6\). Therefore, NMES at 10% of MVIC torque level caused less pain. In addition, NMES at 10% of the MVIC torque level could not affect EMG activity and all phases of RFD. Sang et al.\(^{77}\) indicated that neural activity and the muscle potentiation effect using muscle pre-contraction depend on contraction strength. Therefore, it is assumed that neural and/or muscular activity effects could not observe with even the use of NMES because the 10% contraction strength was more insufficient.

A limitation of this study is that we did not determine the duration of the RFD potentiation effect after 20% NMES. Previous studies have shown that pre-contraction using MVIC lasts about 3 to 5 minutes for the potentiation effect\(^{21}\). Therefore, pre-contraction with 20% NMES is expected to have the possibility of the same results. Future studies, however, should be performed to determine the likelihood of duration effect.

4. Conclusion

Muscle contraction using NMES at 20% of the MVIC torque level for 5 seconds increased EMG activity and 30-, 50-, and 100-msec of RFD, but could not increase the 200 msec of RFD during MVIC. Considering the results may have been caused by neural activation. In contrast, NMES at 10% of the MVIC torque level for 5 seconds caused less pain than NMES at 20% of the MVIC torque level, but not increase EMG activity and all phase of RFD. These results suggest that muscle contraction using NMES at 20% of the MVIC torque level for 5 seconds could induce moderate pain but could be an effective intervention to improve RFD for young adults.

Conflict of Interest: None of the authors has any conflict of interest to disclose.

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References

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