The effects of very high stimulation frequency on fatigue of the quadriceps femoris muscle in healthy participants: A pilot study

ผลของการกระตุ้นด้วยกระแสไฟฟ้าความถี่สูงมากต่อการล้าของกล้ามเนื้อ quadriceps femoris ในผู้ที่มีสุขภาพดี: การศึกษานำร่อง

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ABSTRACT

Background: The main limitation of neuromuscular electrical stimulation (NMES) is the muscle fatigue. According to previous studies, stimulation frequency has the greatest influence on rate of muscle fatigue. However, most of studies have been focused on high stimulation frequency but less than 100 Hz. We proposed that using a very high frequency may produce asynchronous motor unit recruitment and similar or less muscle fatigue.

Objectives: To examine the effects of very high (150 and 200 Hz) and low (50 Hz) stimulation frequencies on the declining stimulated muscle force.

Methods: Nine healthy participants underwent a fatigue test using 3 stimulation frequencies (50, 150, and 200 Hz) combined with wide pulse duration (0.9 ms) for 15 minutes fatigue test. Muscle fatigue was assessed using the normalized force values at the end of each stimulation frequency protocol.

Results: No difference in muscle fatigue was found when compared between very high frequency (150-200 Hz) and low frequency (50 Hz) combined with wide pulse duration conditions during a 15-minute fatigue test.

Conclusion: This study demonstrated that both very high and low frequencies combined with wide pulse duration showed no differences in muscle fatigue. Further studies with a larger sample size are needed for confirmation.

Keywords: stimulation frequency, muscle fatigue, neuromuscular electrical stimulation, quadriceps femoris, muscle force

บทคัดย่อ

ที่มาและความสำคัญ: ข้อจำกัดที่สำคัญในการกระตุ้นเส้นประสาทและกล้ามเนื้อด้วยกระแสไฟฟ้า (NMES) คือการเกิดการล้าของกล้ามเนื้อซึ่งการศึกษาที่ผ่านมาพบว่าความถี่ที่ใช้ในการกระตุ้นมีอิทธิพลต่ออัตราในเกิดการล้าของกล้ามเนื้อ อย่างไรก็ตามการศึกษาส่วนใหญ่มุ่งเน้นไปที่ความถี่ต่ำกว่า 100 Hz ผู้วิจัยมีสมมติฐานว่าการใช้ความถี่สูงมาก อาจทำให้เกิดการระดมของหน่วยประสาทยนต์แบบไม่พร้อมกัน และเกิดการล้าไม่ต่างหรือน้อยกว่า

วัตถุประสงค์: เพื่อศึกษาผลของการกระตุ้นไฟฟ้าโดยใช้ความถี่สูงมาก (150 และ 200 Hz) และความถี่ต่ำ (50 Hz) ต่อการลดลงของแรงการหดตัวของกล้ามเนื้อที่ถูกกระตุ้น

วิธีการ: อาสาสมัครสุขภาพดีจำนวน 9 คนได้รับการทดสอบการล้าของกล้ามเนื้อโดยใช้ความถี่ในการกระตุ้น 3 ช่วงได้แก่ 50, 150 และ 200 Hz ร่วมกับการใช้ช่วงกระตุ้นกว้าง (0.9 ms) เป็นเวลา 15 นาที การล้าของกล้ามเนื้อประเมินโดยใช้ค่าแรงหดตัวของกล้ามเนื้อ (normalized force) เมื่อสิ้นสุดโปรแกรมการทดสอบในแต่ละความถี่

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ผลการศึกษา: ไม่พบความแตกต่างของการล้าของกล้ามเนื้อเมื่อเปรียบเทียบระหว่างการกระตุ้นที่ใช้กระแสไฟฟ้าความถี่สูงมาก (150 และ 200 Hz) และความถี่ต่ำ (50 Hz) ร่วมกับการใช้ช่วงกระตุ้นกว้าง ในการทดสอบการล้านาน 15 นาที

สรุปการศึกษา: การศึกษาครั้งนี้แสดงให้เห็นว่าการกระตุ้นไฟฟ้าโดยใช้ความถี่สูงมากและความถี่ต่ำร่วมกับการใช้ช่วงกระตุ้นกว้างมีผลต่อการล้าของกล้ามเนื้อไม่แตกต่างกัน การศึกษาเพิ่มเติมเพื่อยืนยันผลในกลุ่มอาสาสมัครขนาดใหญ่เป็นสิ่งจำเป็น

Introduction

Neuromuscular electrical stimulation (NMES) is commonly used in rehabilitation programs to increase strength in healthy individuals and individuals with neurological impairment.[1–4] The target force output during electrical stimulation depends on the current parameters, especially pulse duration, stimulation intensity and frequency. Although, NMES has been demonstrated to have benefit in strengthening[4], muscle fatigue are the main limitation during NMES application.[5] Therefore using optimal current parameters that generates stronger force output and minimizes muscle fatigue are essential in clinical treatment.

Previous studies not only have shown that the higher stimulation frequency (60-100 Hz) generated stronger muscle contraction compared to the lower stimulation frequency (20-25 Hz), but also increased rate of muscle fatigue.[6–8] On the contrary, a study of Matsunaga et al[9] showed that high frequency stimulation (100Hz) produced less muscle fatigue than low frequency stimulation (20 Hz). Russ et al[10] demonstrated that the percentage of decline in peak force during the fatigue test was similar between 80 Hz and 100 Hz protocols, if the initial force was controlled. Thus, the relationship of frequency-fatigue remains inconclusive. Moreover, the term low or high stimulation frequency is relatively ambiguous. Most of previous studies[6,7,9,10] defined lower stimulation frequencies in the range of 11-50 Hz and higher stimulation frequencies of 60 or 100 Hz. There is no previous research using the very high stimulation frequency especially higher than 100 Hz to test the fatigue effect.

In addition, most of the previous researches used a short PD (0.05-0.45 ms) to evaluate the effect of frequency on stimulated muscle force.[11–13] Using a wide PD (0.5-1 ms), high frequency demonstrated a higher stimulated muscle force than expected by the direct activation of motor axons.[14,15] This increasing stimulated force output that arises in addition to the direct response to motor axon stimulation has been referred to as from the central contribution which is similar to the natural recruitment pattern.[14,15] However, the central contribution can be elicited only by a low stimulation intensity (10-20% of MVC).[16] Martin et al[16] demonstrated that wide PD combined with high frequency (1 ms, 80 Hz) and low intensity protocol was a similar decrease in stimulating force compared with short PD with low frequency (0.05 ms, 20 Hz) after repetitive electrical stimulation protocol.

Thus, this study used a wide PD (0.9 ms), very high frequency (150 and 200 Hz) and low current intensity (10-20% MVIC) to explore the effects of very high stimulation frequency on muscle fatigue. Based on physiological knowledge, the stimulation frequency which nerve and muscle can respond to stimuli depends on the duration of the refractory period.[17] Because the stimulus which stimulates at the absolute refractory period will not produce any action potential, thus the muscle fiber will not contract.[17,18] We proposed that electrical stimulation using very high stimulation frequency (more than 100 Hz) may asynchronously stimulate motor units if the motor axon is stimulated at the refractory period. Thus, the very high stimulation frequency (150 and 200 Hz) was chosen in this study, based on the reported refractory period of human nerve.[19,20] For the frequency of 150 and 200 Hz, the pause duration between each pulse was varied from 5.77 and 4.10 ms, respectively. This duration may be short enough to stimulate a motor axon in the refractory period of human nerve.[19,20]

Therefore, the purpose of this study was to examine the effects of very high (150 and 200 Hz) and low or conventional (50 Hz)[4] stimulation frequencies with a wide PD (0.9 ms) on the decline in stimulated muscle force. We proposed that using very high stimulation frequency (150 and 200 Hz) would produce similar or less muscle fatigue than using low stimulation frequency (50 Hz).

Methods

Participants

Nine healthy participants (3 males and 6 females; age range 18-35 years) took part in this study. All participants had no history of lower extremity musculoskeletal, neurological or other diseases that might affect the contraction of muscle. They were informed of the research procedures and risks before signing a consent form. This study was approved by the ethics committee of the Faculty of Associated Medical Sciences, Chiang Mai University (AMSEC-58EX-034).

Procedures

All participants were asked to refrain from strenuous physical activities for at least 48 hours before taking part in the study. Each participant undertook in three sessions. The first session included the maximum voluntary knee extensor isometric contraction (MVIC) test, familiarization with the fatigue test protocol and the fatigue test. During the second and third session, one other stimulation frequency was tested, respectively. Each session was separated by at least 48 hours or until there was no perceived muscle soreness. The flowchart of the study procedures is shown in figure 1

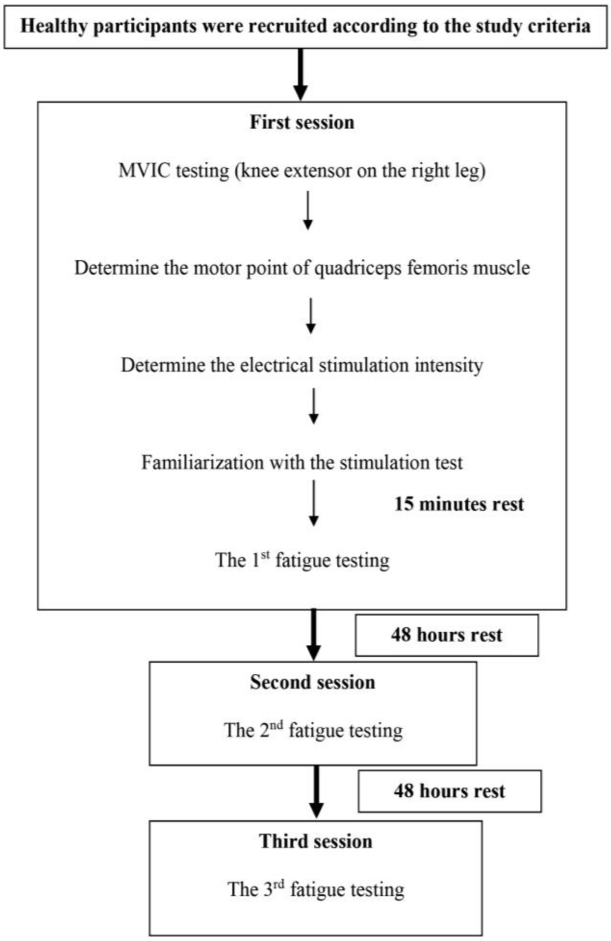

Figure 1 The flowchart of the study procedures

The MVIC of the knee extensor muscle of the right leg was determined in each participant. It was measured using a force transducer (model MLT003/D, ADInstrument Ltd, Australia) which was connected to a PowerLab® System (ADInstrument Ltd, Australia). The force transducer was placed anteriorly on the leg, approximately 15-20 cm proximal to the lateral malleolus, and calibrated by a standard weight mass. All of the participants were seated in a back support and height adjustable chair with the knee flexion at 60 degrees. They were asked to perform 3 trials of knee extensor isometric contractions, and the greatest peak force was recorded as the MVIC of knee extensor muscles, and used as the reference for calculating the percentage of maximum force produced during the fatigue test. After testing the MVIC, stimulation intensity was determined in all of the participants, which produced approximately 10-20% of MVIC, depending on the participants' tolerance for each frequency. This intensity was used in the fatigue test. This initial force (%MVIC) was controlled across the frequency of stimulation.

A 10.5x7.0 cm rubber carbon electrode was placed over each motor point of the rectus femoris and vastus medialis. A rectangular biphasic pulsed current, with a PD of 0.9 ms, frequency of 50, 150 or 200 Hz, and 2 s on time and 4 s off time was used (Phyaction Guidance E, Uniphy International, Holland). After determining the stimulation intensity, each participant became familiarized with the stimulation test, using 50, 150 and 200 Hz for a few minutes.

Following familiarization, a 15-minute rest period was taken to avoid muscle fatigue before the fatigue test. One of three stimulation frequencies (50, 150 or 200 Hz) was applied randomly to the quadriceps femoris muscle of the right leg.

The knee extensor isometric force outputs, produced by electrical stimulation, were recorded at the sampling rate of 1,000 Hz using the PowerLab® System (ADInstrument Ltd, Australia).[21]

Outcome measure

Muscle fatigue is defined as a comparison between the decline and initial stimulated force of an individual. Each stimulated force was determined by averaging the maximum stimulated force, which was sampled every second over a 2-s contraction time. Then, every 5 contractions of these stimulated forces were averaged and used for further data analysis. Thus, 30 data points of stimulated force from a 15-minute fatigue test were normalized to each participant's initial force and compared with each stimulated frequency.

Statistical analysis

Normal distribution of data was analyzed using the Shapiro-Wilk test. A one way repeated measures analysis of variance (ANOVA) with a Bonferroni test was used to determine the significant differences of normalized force values at the end of a fatigue test, and current amplitude of each frequency. The Friedman's test was used to determine the significant differences of muscle contraction intensity (%MVIC) at the beginning of each fatigue test. Statistical significance was set at a level of $p < 0.05$. Partial η^2 value was reported as measure of effect size (ES) for difference in the normalized force values at the end of each fatigue test. The SPSS version 17.0 for Windows was used for analysis of data.

Results

Nine participants (3 males, age = 24.11 ± 3.33 year with MVIC = 292.44 ± 82.80 N) were volunteered. Table 1 shows mean and standard deviation of the current amplitude and the % MVIC in each stimulation frequency. The current amplitude, which provided approximately 10-20% of MVIC, was greatest at 50 Hz when compared to 150 and 200 Hz. However, these differences were not statistically different among the three stimulation frequencies (p=0.051). The %MVIC of average peak forces at the beginning was slightly greater at the 150 and 200 Hz stimulation frequencies than that at the low stimulation frequency, but without statistical significance (p=0.459). All stimulation frequencies showed a similar decline in normalized stimulated force during the 15 minutes fatigue test (Figure 2). The normalized forces (Table 2) were not significantly different among the three stimulation frequencies (50, 150 and 200 Hz) at the end of the fatigue test (p=0.801; ES = 0.027).

Table 1 The mean and standard deviations of the current amplitude and % MVIC of average peak forces at the beginning (n=9)

Variables	50 Hz	150 Hz	200 Hz	*p*-value
Current amplitude (mA)	44.22 ± 11.86	38.00 ± 11.19	38.78 ± 13.50	0.051
% MVIC of average peak forces at the beginning	12.85 ± 6.16	16.44 ± 6.27	15.37 ± 7.12	0.459

MVIC, Maximal voluntary isometric contraction

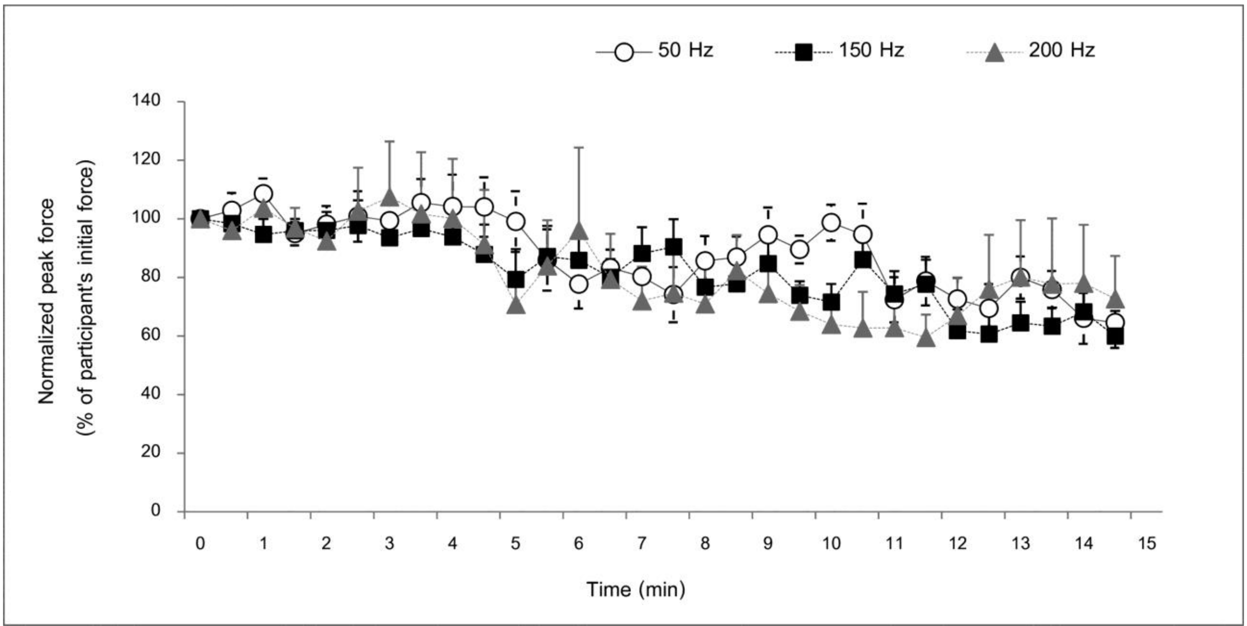

Figure 2 The decline in normalized stimulated force during a-15 minute fatigue test. Data are presented as mean, error bars represent SEM

Table 2. The normalized force (mean ± SD) at the end of the fatigue test in each stimulation frequency

Frequency (Hz)	Normalized force at the end of the fatigue test (% of participant's initial force)
50	64.57 ± 42.76
150	59.95 ± 25.78
200	72.70 ± 43.84

Discussion

The present study was the first to compare the effects of very high (150 and 200 Hz) and low (50 Hz) stimulation frequencies on the decline in stimulated muscle force of quadriceps femoris muscle in healthy participants. We expected that using very high stimulation frequency (150 and 200 Hz) may asynchronously recruit motor units and would produce similar or less muscle fatigue than using low stimulation frequency (50 Hz). Our results found that the decline in stimulated force at the end of fatigue test was similar for all stimulation frequency conditions. The finding of the present study is supported by the study of Russ et al[10] which demonstrated that the percent declines in peak force during the fatigue test was similar for 80 Hz and 100 Hz protocols. Although, the study of Matsunaga et al[9] which found lesser declined in force during fatigue test at the high stimulation frequency (100 Hz) compared to low stimulation frequency (20 Hz) in healthy subjects. However, the off time between contractions in the present study was shorter than in Matsunaga et al's study[9] (4 s versus 60 s, respectively).

Contrary to our findings, Dreibati et al[7] demonstrated that decreased muscle force at the end of the fatigue session was lesser for the low stimulation frequency (20 and 50 Hz) compared to high stimulation frequency (100 Hz). Compared with our study, the fatigue protocol tested by Dreibati et al[7] used much shorter PD (0.3 ms versus 0.9 ms in the present study). Thus, a possible explanation for the difference between findings is that the different stimulation parameters setting, that is, frequency and pulse duration, during repetitive electrical stimulation were used. It may be possible that wide PD would increase the central contribution which is similar to the natural recruitment pattern. Therefore, wide PD may minimize muscle fatigue when compare to short PD. However, previous studies[14,22] reported that the central contribution from wide pulse stimulation was demonstrated only in some participants. The variability of the central contribution requires further study.

The present study using different combinations of frequency and wide PD (0.9 ms) during the fatigue test, so it is difficult to compare with the results of Kesar and Binder-Macleod.[6] However, the similar decline of stimulated force during repetitive stimulation in our study showed a similar trend to the finding of Martin et al [16] which using 80 Hz with 1 ms PD protocol compared with 20 Hz with 0.05 ms PD. Kesar and Binder-Macleod[6] used 60 Hz with 600 μs PD as the testing train and found the same decline in peak force between the low frequency (11 Hz 600 μs PD) and the high frequency (60 Hz 130 μs PD). The findings of Kesar and Binder-Macleod strongly suggested that the combinations of PD and frequency may effect on muscle fatigue during repetitive stimulation.

The advantage of using very high stimulation frequency is that the high frequency used current intensity smaller than the low frequency for generating muscle contraction and could generate the rapid muscle contraction.[9] Therefore, therapists may apply very high stimulation frequency combined with wide PD as an optional parameter for NMES application. However, the present study did not compare discomfort level between high and low stimulation frequency protocols, thus the advantage in aspect of muscle force contraction and discomfort level should be confirmed in further study. Another limitation of this study is that the findings of this study were obtained from a small sample size of healthy individuals. In addition, further studies need to be performed on patients with quadriceps femoris muscle weakness.

Conclusion

This pilot study demonstrates that no difference in muscle fatigue was found when compared between very high frequency (>100 Hz) and low frequency (50 Hz) combined with wide pulse duration (0.9 ms) conditions during the repetitive electrical stimulation. Further studies with a larger sample size are needed for confirmation.

Conflicts of interest

The authors have no conflicts of interest relevant to this article.

Acknowledgements

This study was supported by the Faculty of Associated Medical Sciences, Chiang Mai University, Thailand.

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