

Investigation of Different Stimulation Patterns to Reduce Muscle Fatigue during Functional Electrical Stimulation

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Abstract—Functional electrical stimulation (FES) is a commonly used technique in rehabilitation and often associated with rapid muscle fatigue which becomes the limiting factor in its applications. The objective of this study is to investigate the effects on the onset of fatigue of conventional synchronous stimulation, as well as asynchronous stimulation that mimic voluntary muscle activation targeting different motor units which are activated sequentially or randomly via multiple pairs of stimulation electrodes. We investigate three different approaches with various electrode configurations, as well as different patterns of stimulation applied to the gastrocnemius muscle: Conventional Synchronous Stimulation (CSS), Asynchronous Sequential Stimulation (ASS) and Asynchronous Random Stimulation (ARS). Stimulation was applied repeatedly for 300 ms followed by 700 ms of no-stimulation with 40 Hz effective frequency for all protocols. Ten able-bodied volunteers (28±3 years old) participated in this study. As fatigue indicators, we focused on the analysis of Normalized Fatigue Index (NFI), Fatigue Time Interval (FTI) and pre-post Twitch-Tetanus Ratio (Δ TTR). The results demonstrated that ASS and ARS give higher NFI and longer FTI confirming less fatigue for asynchronous stimulation. In addition, ASS and ARS resulted in higher Δ TTR than conventional CSS. In this study, we proposed a randomly distributed stimulation method for the application of FES and investigated its suitability for reducing muscle fatigue compared to previously applied methods. The results validated that asynchronous stimulation reduces fatigue, and indicates that random stimulation may improve fatigue resistance in some conditions.

Keywords—Asynchronous stimulation, electrode configuration, functional electrical stimulation, muscle fatigue, pattern stimulation, random stimulation, sequential stimulation, synchronous stimulation.

I. INTRODUCTION

FES is one of the techniques that have been used in rehabilitation as therapy for those with Spinal Cord Injury (SCI). FES involves electrical stimulation to activate paralyzed muscles and is used in a wide range of assistive and therapeutic applications in neurorehabilitation.

A primary purpose of FES is to cause muscle contraction so that functional movement can be produced in a paralyzed muscle by restoring or enhancing the lost motor functions in people affected by many neurological disorders such as SCI, stroke, multiple sclerosis, or cerebral palsy. Inducing electrical

stimulation typically leads to rapid muscle fatigue. Current exercise systems that are implemented with FES are limited in their effectiveness by this rapid fatigue which may be related to the nature of the stimulation patterns.

There are numbers of previous solutions which have been proposed to reduce muscle fatigue during FES, including diversifying the pattern of stimulation [1]–[5]. Recent studies indicate that asynchronous distributed stimulation can be a potential solution for reducing muscle fatigue during FES [6]–[8]. However, to our knowledge, there is no recent study that investigates the potential of partial and sequential randomly distributed stimulation patterns on muscle fatigue resistance during FES compared to conventional method of FES.

High frequency of stimulation may provide high force and smooth contraction. But, prolonged contraction with high frequencies increases the rate of muscle fatigue. Lowering frequencies may reduce the muscle performance by decreasing the force of contraction and the contraction itself may become less smooth. Using multi-electrodes with low frequency stimulation may resolve this situation where asynchronous low-frequency is distributed within multi-pad electrodes with contraction comparable to the force elicited with a single-pad electrode activated with high frequency [7], [9]–[11]. The stimulation will be distributed to more portion of muscle with low frequency that will produce the high force which is comparable with the high frequency of stimulation. An extension to sequentially stimulating multiple electrodes is to activate them in random. This approach may have its own potential in preventing rapid fatigue during FES application. We therefore propose low frequency distributed via multiple electrodes with random stimulation to reduce muscle fatigue during FES. The aim of this study is to investigate the efficiency of sequential and random asynchronous stimulation compared to CSS during FES.

II. PROCEDURE

A. Subjects

A group of 10 able-bodied volunteers (3 male, 7 female, 28.3 ± 3.2 years (mean ± std dev)) participated in this study which was approved by the University of Glasgow ethics committee, and all participants gave written informed consent. Each participant attended three sessions, with each session separated from the other by at least 24 hours to ensure that fatigue from the previous session did not affect the next

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session. The sequences of the fatigue trials described below are randomized in each session.

B. Apparatus & Data Acquisition

The FES Stimulator used in this study is the Rehaslim v1 (Hasomed GmbH, Germany) with 2.5 cm x 4.5 cm electrodes (PALS Platinum Axelgaard, USA), controlled by a PC via a USB interface. A custom-made force platform was used to measure ankle torque which was recorded via a data acquisition board (DAQ-6024E, National Instruments, USA) with a sample frequency of 200 Hz. Fig. 1 shows the schematic diagram of the experimental setup for this study.

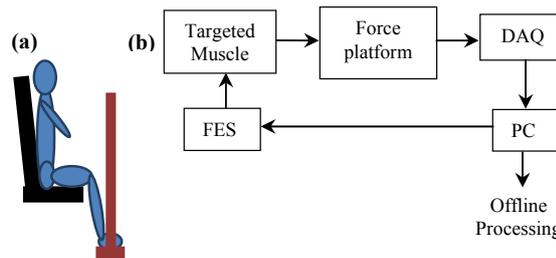


Fig. 1 The schematic diagram of the experimental setup in (b) and the subject are in sitting position attached to the custom-made force platform under the feet with ankle position 90° as shown in (a)

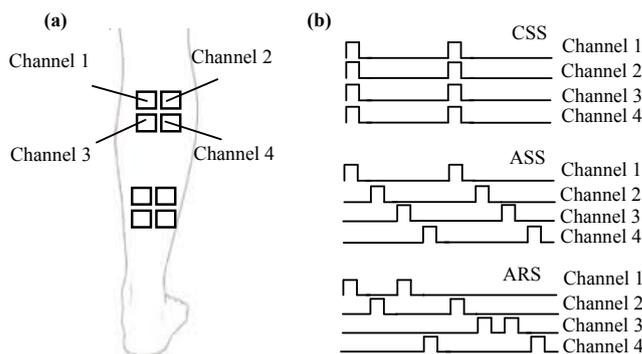


Fig. 2 Three types of stimulation protocols used in this study. The electrodes positioning shown in (a) fixed to all protocols. Stimulation pulses in (b) represent the stimulation protocols for synchronous (CSS) and asynchronous (ASS and ARS) stimulation

C. Stimulation Protocol

Three stimulation protocols were examined to compare the torque changes over 600 s. The stimulation pulse width was set at 300µs for all protocols [12]. The stimulation current was set individually, as high as was tolerated by each participant. The effective frequencies were set up to 40 Hz for all protocols (1 channel stimulation (CSS): 40 Hz; 4 channels stimulation (ASS and ARS):10 Hz for each channel) [6]. The electrodes positions are shown in Fig. 2. For CSS, all channels were effectively combined into one single channel of FES.

D. Experimental Procedure

Each protocol has four sub-sessions (current intensity selection, pre-fatigue test, fatigue trial, and post-fatigue test). Fig. 3 shows details the procedure for each session. The maximum voluntary contraction (MVC) were performed once at the beginning of the first session.

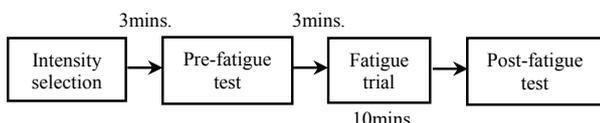


Fig. 3 The experimental procedure for each protocol. Rest time after each sub-session was given to prevent from fatigue affection

1. Intensity Selection

Each session began with current intensity selection where the current intensity was adjusted from minimum value and increased in steps of 2 mA until the maximum torque as maximum voluntary contraction (MVC, i.e. (desired torque)) or maximum tolerable stimulation intensity is reached.

2. Pre-Fatigue Test

The pre-fatigue trial consists of a single stimulation pulse followed by a short burst of stimulation 10 s later. This allows a twitch-tetanus ratio to be calculated.

3. Fatigue Trial

Fatigue trials consisted of 600s of intermittent stimulation where each pulse train was delivered for 300ms on and 700ms off.

4. Post-Fatigue Test

The post-fatigue trial has the same procedure as pre-fatigue trial and was delivered just after fatigue trial without any rest time to assess immediate fatigue.

E. Data Analysis

This study focuses on three fatigue indicators: NFI, FTI, and ΔTTR. To account for intersubject variability in strength and intrasubject variability in the initial contraction, all amplitudes were normalized to the mean of the first 10 stimulation trains. NFI is defined as the normalized mean of the last 20 trains while FTI is defined as the time at which the

normalized torque decreased to 80 % of the initial contraction [8]. Δ TTR is the percentage change in the twitch-tetanus ratio between pre-fatigue and post-fatigue trials. Analysis of

variance (ANOVA) was performed for NFI, FTI, and Δ TTR at the significant level of $\alpha=0.05$.

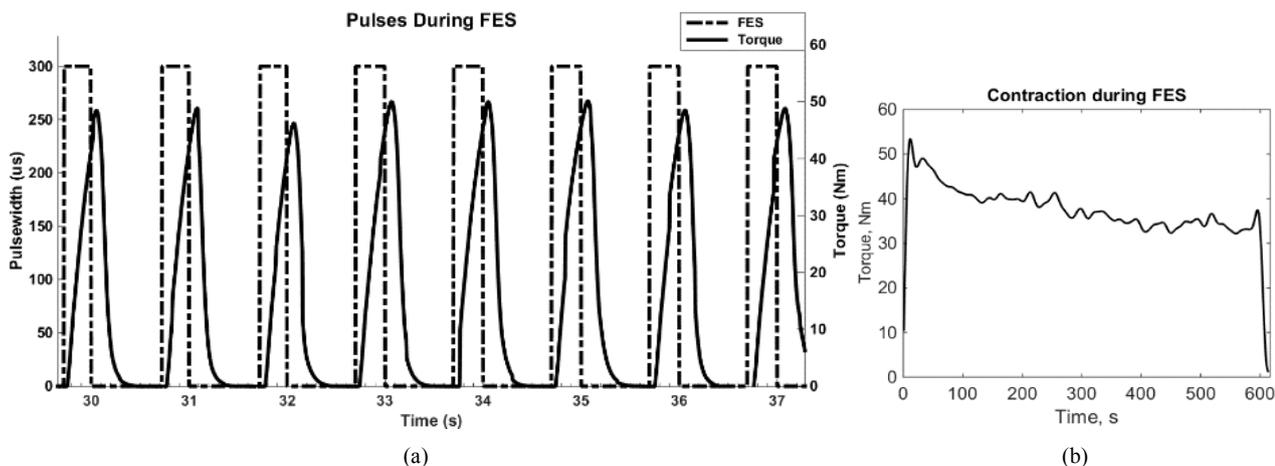


Fig. 4 Pulses and contraction during FES: (a) The FES pulses with ON and OFF stimulation pattern (b) The contraction for one subject shows decreasing torque over 600s of FES

III. RESULTS

The results obtained from applying the three fatigue protocols to all 10 subjects are shown in Tables I and II. Examples of the FES pulses and contractions recorded from one subject are shown in Fig. 4.

The average contraction shown in Fig. 5 represents the mean normalized torque across all participants. The last contraction number, representing the NFI (mean of last 20 trains), shows a larger decrease for CSS (24 %) compared to ASS (4 %) and ARS (8 %).

Mean NFI and Twitch-Tetanus Ratio (Δ TTR) are shown in Table I and individual FTI obtained from the three fatigue protocols are shown in Table II.

IV. DISCUSSION

In this study, we investigated three different stimulation patterns for reducing muscle fatigue during FES. In all stimulation patterns, we compared the NFI (mean of last 20 trains of contraction over initial 10 trains), FTI (time before the torque decline below 80 %) and Δ TTR (the ratio of twitch and tetanus for pre-fatigue and post-fatigue) as a fatigue indicator using multi electrodes and intermittent FES stimulation.

Asynchronous stimulation resulted in higher NFI than synchronous stimulation with ARS yielding a value 23.1 % higher than CSS, while ASS resulted in a value 3 % higher than ARS and 26.8 % higher than CSS ($p<0.05$). Hence, both asynchronous protocols show higher fatigue resistance than CSS.

Asynchronous stimulation also resulted in longer FTI than synchronous stimulation with ARS yielding a 10.4 % longer FTI than ASS and 105.7 % longer than CSS. ASS resulted in FTI was 86.2 % longer than CSS. It should be noted that the muscle did not fatigue beyond the 80 % fatigue threshold (8 in

ARS; 6 in ASS; 2 in CSS). As the trial time was limited to 600 s, the real FTIs are likely to be even longer than reported for ASS and ARS.

TABLE I
NFI AND TWITCH TETANUS RATIO \pm SD

Protocol	NFI	Δ TTR
CSS	0.76 \pm 0.13*	90.0% \pm 36%
ASS	0.96 \pm 0.21	97.4% \pm 28.9%
ARS	0.92 \pm 0.15	124.4% \pm 54.2%

* Significantly difference from ASS and ARS ($p<0.05$)

TABLE II
FTI

SUBJECT	CSS (s)	ASS (s)	ARS (s)
1	94	197	600
2	48	538	74
3	250	394	510
4	600	600	600
5	401	600	600
6	42	600	600
7	600	600	600
8	69	600	600
9	74	146	600
10	440	600	600
M	261.8	487.5	538.4**
SD	229.6	178.9	165.6

** Significantly longer FTI than ASS and CSS ($p<0.05$)

Although no significant difference is found for Δ TTR between the different stimulation protocols, asynchronous stimulation resulted in the higher value for Δ TTR as shown in Table I. Higher Δ TTR represents higher tetanus torque at the end of the trial.

The present study validates that asynchronous stimulation gives better performance in reducing muscle fatigue during FES compared to CSS [6], [13], [10].

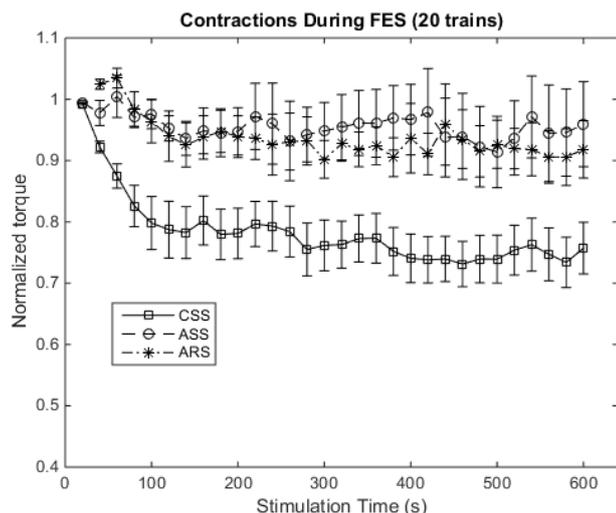


Fig. 5 Contraction during FES in 600s. Each contraction presents the mean of normalized torque (20 trains) produced for all protocol

Both asynchronous stimulations show better performance compared to CSS where higher values for NFI, FTI, and Δ TTR indicate higher fatigue resistance. Our results show similarity with previous studies [6]–[8], suggesting that asynchronous stimulation has a greater fatigue resistance compared to CSS. Furthermore, this study proposed randomly distributed stimulation to compare the performance of fatigue resistance with asynchronous stimulation. Hence, randomly distributed stimulation was shown to have longer FTI which is required for rehabilitation training in SCI population.

V. CONCLUSION

The strategy of asynchronous stimulation shows a great reduction in muscle fatigue during repetitive electrical stimulation. Although randomly distributed stimulation is not a strategy currently used in FES, perhaps it should be considered as one of the potential protocols to reduce muscle fatigue during FES. Future work is needed to develop less pain sensation in randomly distributed stimulation to benefit in longer rehabilitation training during FES.

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