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Functional electrical stimulation-induced muscular fatigue: Effect of fiber composition and stimulation frequency on rate of fatigue development

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A R T I C L E I N F O

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A B S T R A C T

This investigation evaluated the progression towards fatigue in two muscles of differing fast- and slow-twitch fiber proportions (abductor pollicis brevis (APB) and vastus lateralis (VL)) when activated by functional electrical stimulation (FES) at three frequencies (10, 35, and 50 Hz). Fatigue was defined as a 50% drop from the initial FES-induced force of 25% maximal voluntary contraction (MVC). Ten healthy adults (mean age: 23.2 ± 3.0 years) were recruited; participants signed an IRB approved consent form prior to participation. Protocols were developed to evaluate the effects of muscle size, fiber type and FES frequency on total time to fatigue. Results indicated that the predominantly fast-twitch VL fatigued more quickly than the slow-twitch APB at the higher frequencies ($p < 0.05$), but did not significantly differ with stimulation at 10 Hz. Overall, muscle size and FES frequencies showed some significant interactions when generating a defined force and during fatigue development. Furthermore, it appears that to reduce fatigue, FES treatments should not extend past ~14–16 min for large and small muscle groups, respectively, when the muscle group's optimal stimulation frequency is applied.

1. Introduction

Applications of functional electrical stimulation (FES) have achieved positive responses at the cellular level, contributing to overall biomechanical enhancement and tissue regeneration. At the cellular level, accelerated rat and dog tendon healing was accomplished with FES by promoting greater blood flow and fibroblast number to the injured region (Ekaputra et al., 2011; Jabbarzadeh et al., 2008). Moreover, FES was reported to reverse long-term denervation muscle atrophy and dystrophy via increasing myofiber diameter size by more than ~50% and regenerating new myofibers (Kern et al., 2004). In addition, the integration of FES with a traditional volitional isometric training program, as utilized by individuals during post-anterior cruciate ligament repair, has been shown to be more effective at improving muscle function and preventing atrophy after five weeks compared to isometric training alone (Eriksson and Häggmark, 1997).

These findings highlight the potential for FES as a key component for effective muscle tissue regeneration and repair, as well as prevention of muscle atrophy. However, human musculature consists of tissue that varies in size, fiber composition, and fiber arrangement; therefore, these specific characteristics should be considered when determining the appropriate application of FES.

FES-induced activation reportedly initiates fiber recruitment in reverse order to the pattern of recruitment observed during voluntary activation, leading to faster fatigue development as more type II fibers are utilized earlier than with volitional control (Estigoni et al., 2014; Morf et al., 2015). Research inclusive of predominately type I muscles mostly assessed the tibialis anterior (TA), first dorsal interosseous (FDI), and abductor pollicis brevis (APB) while research inclusive of predominately type II muscles mostly assessed the biceps brachii (BB) and knee extensors (vastus lateralis (VL), vastus medialis, rectus femoris), but to our knowledge research has rarely examined fatigue development with consideration of fiber type variability and FES frequency together in the same sample population.

Furthermore, several studies have examined the manipulation of FES parameters (frequency, intensity, pulse width, duty cycle) in relation to fatigue development, finding frequency to be the only component associated with fatigue (Behringer et al., 2015; Gorgey et al., 2009). It has been reported that lower frequencies are preferred for FES as they are less fatiguing on the muscle than higher frequencies (Alexandre et al., 2015). Moreover, frequencies below 40–50 Hz recruited more slow-twitch, type I fibers, that are more fatigue-resistant, while higher frequencies recruited more fast-twitch, type IIa and IIb fibers, that fatigue more easily (Dreibati et al., 2010). Stimulation with

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frequencies ranging from 20 to 100 Hz caused the percentage of maximum voluntary contraction (MVC) force to drop by 40–50% after five minutes and by nearly 60% after ten minutes. For this reason, it was suggested that FES training protocols not to extend beyond 20 min of active FES and, with sports or clinical rehabilitation, a protocol of five minutes of FES spaced by ten minutes of rest, repeated four times maximally, is more effective in preventing fatigue (Dreibati et al., 2010).

Experimentally, fatigue development was most often defined by changes in force measures related to baseline MVC force when FES treatment was selected for a given duration or particular number of contractions (Bickel et al., 2004; Chesler and Durfee, 1997; Chou and Binder-Macleod, 2007; Gregory et al., 2007). However, others have used gradual declines in force during FES as markers of fatigue, such as a 50% drop in force from the initial force induced by FES (Behringer et al., 2015). Additionally, electromyography (EMG) has been used to evaluate fatigue by monitoring changes in the electrical activity of the muscle. By utilizing both force changes and EMG during FES, the understanding of fatigue progression is enhanced. Muscle electrical activity measures are obtained through several calculations including the root mean square average (RMS) and median frequency (MDF) (Chesler and Durfee, 1997; Gonzalez-Izal et al., 2014; Tepavac and Schwirtlich, 1997).

Ultimately, understanding the response of muscles that differ in fiber composition to alternate FES stimulation frequencies may help develop better muscle-specific FES protocols aimed to prevent fatigue and improve muscle recovery. The purpose of the present investigation was to determine the rate of fatigue development under the application of different FES frequencies in muscles of differing fiber compositions. Specifically, we aimed to (1) evaluate and compare changes in the force and electrical activity of each muscle pre- and post-fatigue and (2) evaluate time to fatigue at different stimulation frequencies for each muscle. It was hypothesized that force and electrical activity measures from EMG will decline as fatigue develops and that lower frequency FES will produce longer time to fatigue for both muscles. Furthermore, the VL will fatigue more quickly than the APB overall, emphasizing the need for consideration of fiber composition and muscle size when implementing FES as opposed to a 'one size fits all' approach.

2. Methods

2.1. Participants

Ten healthy male and female participants (23.2 ± 3.0 years) with no known history of musculoskeletal or cardiovascular problems, or known allergy to surface electrodes or adhesive tape were recruited. Full-board IRB approval and written consent was obtained prior to participation.

2.2. Instruments

FES was delivered using the Respond Select® (Empi, Inc., St. Paul, Minnesota) neuromuscular electrical stimulation system. Self-adhesive, reusable, latex-free bipolar stimulating surface electrodes (90 × 50 mm square for VL; 3.5 cm round for APB) were placed on the skin following Empi, Inc. guidelines and connected to the FES device for muscle activation (Fig. 1 – images on the far right).

EMG signals were acquired through the Nexus-10 EMG device (MindMedia B.V., Netherlands). Sampling frequency was set at 2048 Hz. Pre-gelled, self-adhesive Ag/AgCl EMG surface electrodes (4 × 2.2 cm figure 8-shaped, 1.75 cm inter-electrode distance, Noraxon USA Inc., Scottsdale, AZ) were placed across the muscle belly in parallel with the muscle fibers according to Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles (SENIAM) guidelines.

Isometric forces for the APB were measured using the PasPort high resolution force sensor (range: ± 50 N, resolution: 0.002 N; PASCO Scientific Inc., Roseville, CA) and for the VL using the Shimpo Instruments (ELECTROMATIC Equipment Co., Cedarhurst, NY) Javelin FGV-HXY Force Gauge (maximal capacity: 500 lb/250 kg; accuracy: +/−0.2% F.S.).

2.3. Experimental setup

Protocols were developed for the APB and VL to ensure stabilization and isolation of the related muscles during testing. For APB testing, subjects were seated with the arm in 90° elbow flexion. Hand and forearm muscles were isolated via resting on a horizontal board such that a metal hand guard gently but firmly presses the metacarpals and phalanges against a rigid vertical board, only to let the thumb abduct when stimulated (Stratton and Faghri, 2016). The thumb force sensor was affixed to a rod projecting from the table surface so as to be positioned facing the palm of the hand at thumb height (Fig. 1a). For VL testing, subjects were seated in an upright chair (hips at 90° flexion) as such that feet did not make contact with the ground and the back of the knee joint contacted the edge of the chair. A strap was placed firmly around the waist to isolate the quadriceps and inhibit contribution from other hip flexors and extensors during contraction (Bohannon et al., 2011; Stratton and Faghri, 2016). The force sensor was positioned facing the lower anterior leg, and was affixed from the side of the chair (Fig. 1b).

2.4. Procedure

The order at which the frequencies were delivered and of which muscle was first stimulated was randomized. A familiarization session that introduced appropriate posturing and execution of MVC and FES sensation was given to all participants prior to starting the fatiguing protocol.

2.4.1. Part One: Pre-fatigue MVC

For each muscle at each of three stimulation frequencies (10, 35, and 50 Hz), all participants performed two pre-fatigue MVC trials (holding contraction for 5 s then relaxing) of isometric knee extension and thumb abduction. EMG was simultaneously recorded. Verbal encouragement was offered from the rater. A minimum of 30 s of rest was given between the two trials to allow adequate recovery. The values were averaged and recorded as the preMVC value. The force measure that equated to 25%preMVC was then calculated and a contraction to 25%MVC was performed while the EMG was recorded.

2.4.2. Part Two: FES-induced progression towards fatigue

Prior to the fatiguing protocol for a given FES frequency, each participant's required stimulation intensity value to achieve 25% preMVC force through FES-induced contraction was determined (APB range: 10–29 mA; VL range: 32–63 mA). This value was then set as a constant for the fatiguing protocol and the timer began to record time to fatigue. Each participant was stimulated at a randomized frequency order (10, 35, and 50 Hz) with biphasic pulses delivered at pulse-widths of 300 us. Pulses were delivered at a sequence of 4sON/4sOFF (Behringer et al., 2015). Stimulation concluded when the muscle fatigued, defined as a 50% drop in force from the initial 25%preMVC force for three consecutive contractions (Behringer et al., 2015), or at the expiration of 30 min of FES. The timer stopped once fatigue or 30 min was reached. The FES device was shut-off and each participant again performed two MVC trials (holding contraction for 5 s then relaxing). The average of these two trials was recorded as the postMVC value. EMG was recorded for the postMVC trials.

At least 30 min of rest was given in-between fatiguing protocols applied to the same muscle.