INFLUENCE OF VIBRATION STIMULI APPLIED ON THE QUADRICEPS FEMORIS MUSCLES DURING FUNCTIONAL ELECTRICAL STIMULATION INDUCED CYCLING

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Abstract: *FES-cycling is an approach that is recommended in certain instances to improve muscle strength and mass, blood flow and power output. However, the control of FES-cycling in individuals with movement disorders such as spinal cord injury is challenging. The inherent muscle fatigue related to FES and involuntary muscle spastic activity following injury degrade cycling performance. Therefore, a hybrid rehabilitation strategy to adjust the muscle force-generating capacity is well-motivated to cope with muscle fatigue and spastic behavior. Emergent results have reported the use of vibratory stimuli to induce torque and muscle activity adaptations when applied on the muscle tendon or belly. However, the interaction between muscle vibration and FES during cycling is unknown. In this paper, vibration stimuli were applied on the quadriceps belly concurrently with FES during cycling at 60 RPM. An electric motor assisted to keep the target cadence while the rider received intermittent FES and vibration. Four able-bodied individuals were recruited for two FES-cycling trials with and without vibratory stimuli. The mean active torque, fatigue time and fatigue rate are reported for all participants.*

Keywords: *FES-cycling, Vibration, Torque, Fatigue*

Introduction

Neurological disorders such as spinal cord injury (SCI) result in limited limb coordination, spasticity, and diminished muscle strength. Functional electrical stimulation (FES) has been used to facilitate lower-limb movement and improve muscle mass, muscle strength, bone mineral density, and blood flow [1-2]. However, muscular fatigue develops more rapidly using FES than volitional contractions, limiting the overall effectiveness of FES [3-4]. This phenomenon is due to the reverse recruitment order of motor units (i.e., opposite to the size principle) or recruitment of motor units using a nonselective, synchronous and spatially fixed pattern [5].

Robotic exoskeletons and motorized cycles are combined with FES to assist the user complete a task. An example of such a hybrid system is motorized FES-cycling, where surface electrical stimulation is applied to multiple muscle groups to evoke active torque complemented by the assistance of an electric motor [6]. FES-cycling is recommended for people with upper-limb pathologies and impaired sensory feedback who are excluded from gait training or other high cardiovascular exercises. Motorized assistance enables repetitive practice and aids to delay the onset of muscle fatigue. However, providing more machine assistance than needed can induce passive cycling and reduce the therapeutic benefits of FES. Hence, motivation exists to electrically stimulate the lower-limb muscles for prolonged periods during cycling. However, inevitably muscle fatigue settles, thus inducing a decay in the peak force generated by the muscles. An additional challenge for FES-cycling in individuals with SCI is the physical interference associated with spasticity characterized by muscle spasms and co-contractions. Involuntary muscle spasms limit the duration, intensity and dosage of active cycling. Hence, despite the benefits of FES-cycling, muscle fatigue and physical disturbances resulting from spasms interfere with cycling and degrade the functional gains. There is a need to improve hybrid rehabilitation strategies to cope with these challenges and enable a wider adoption of FES-cycling at home and the community.

Mechanical vibration or vibratory stimuli have been implemented to provide sensory feedback in application to alleviate chronic pain [7], gain muscle power [8], induce muscular activity, improve lower limb kinematics, and enhance conventional resistance exercise gains [9-10]. Customized motor-vibration systems have been designed for grip force testing or upper arm rehabilitation [9] and whole-body vibration (WBV) platforms [10-11]. Moreover, hand-held vibration devices are used to manually apply the vibration over muscles. WBV and local vibration have reduced spasticity and increased muscle activity attributed to reflex activity modulation [12-13]. The vibration frequencies in [12-13] range from low frequencies 20-50 Hz for WBV to high frequencies 300-500 Hz using local vibration devices. Vibration has increased muscle activity, reduced sway while standing, and induced muscle forces when applied to the Achilles tendon [14]. The increase in muscle activity due to vibration has been explained through muscle spindle-induced reflexive recruitment of inactive motor units

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[11,15]. The modulation of afferent inputs achieved through tendon and muscle vibration is known to be a strong stimulus for the activation of muscle spindle primary endings, thereby stimulating sensory and motor cortical areas [15]. However, it is unknown whether vibratory stimuli applied during FES-cycling can influence the force generated by muscles and consequently with muscle fatigue or spastic muscle activity.

In a recent study, constant superimposition tendon vibration had no effects on wide-pulse low frequency neuromuscular electrical stimulation (NMES) applied on the quadriceps during plantar flexion motion [19]. It was suggested that NMES induced saturation of the Ia afferents and, thus, the muscle was over activated. It has been also suggested that vibration may be more effective if it is brief or intense to produce a synchronous afferent flow [20]. Motivation exists to examine how to modulate the vibration timing and magnitude. The objective of the present study is to assess the impact of mechanical vibration in the muscle active torque output during electrically elicited contractions.

In this paper, the goal is to investigate the effects of vibratory stimuli applied to the quadriceps muscle belly during FES-cycling. A wearable garment with vibratory motors is placed on the surface of the quadriceps concurrently with a single-channel synchronous FES on both legs to examine the active torque produced. This paper examines the effects of vibration stimuli applied to the quadricep femoris during dynamic contractions using a similar device as the one developed in [21], which was tested for isometric contractions. Experiments were conducted on four able-bodied individuals to assess the feasibility of the hybrid cycling approach.

Methods

Subjects: Four healthy subjects (aged 24.25 ± 5.25 years) participated in the study. Each participant gave written informed consent to enroll in the study, as approved by the institutional review board at Syracuse University. All the participants had prior experience with similar FES-cycling protocols but not with the application of vibratory stimulus.

Apparatus: The testing apparatus consists of a recumbent cycle (Sun Seeker ECO-TAD SX) mounted on an indoor trainer, adapted with orthotic boots, and equipped with a 24 VDC brushed electric motor. A torque transducer (SRM, Germany) was utilized to measure the cycle crank torque. An optical encoder (US Digital) was coupled to the cycle crank to measure the crank position. A data acquisition device (Quanser QPIDe, Quanser, Canada) was used with a personal computer executing MATLAB/Simulink 2018a (MathWorks Inc) for data logging with a sampling rate of 1 kHz. An analog motor driver (Advanced Motion Controls) commanded the current control to the electric motor.

Biphasic symmetric rectangular stimulation pulses were delivered by a current controlled electrical stimulator (RehaStim, Hasomed GmbH, Germany). A single stimulation channel was used with a pair of 3” by 5” bipolar self-adhesive surface electrodes placed over the distal-medial and proximal-lateral portions of the quadriceps muscle group on both legs [surface electrodes for the study were provided compliments of Axelgaard Manufacturing Co., Ltd. (ValuTrode®, USA)]. The mechanical stimulus was applied to the quadriceps muscle belly using vibratory motors of 9 mm diameter (Pico VibeTM, Precision Microdrives, United Kingdom) affixed to the leg using an adjustable garment. Each vibratory motor was controlled by applying a 3V voltage command to achieve a frequency of 230 Hz, which was perceptible, and a vibration amplitude of 7g (g-force or acceleration of gravity). Six vibration motors were used to apply the vibratory stimuli bilaterally. The garments were secured to the participant’s thighs using Velcro straps to provide an appropriate fit and ensure direct contact between the vibration motors and the muscle belly. The placement of the garment with the vibration motors and FES electrodes is depicted in Fig. 1.

FES and Vibration Protocols: A pretrial cycling test was conducted on a separate day and prior to the main cycling trials to determine the pulse width for each participant (and to prevent influencing the results of the subsequent cycling trials). The pretrial test was performed at 60 revolutions per minute (RPM) with motorized assistance. The pulse width was selected as the minimum to evoke an active torque output of 4 N·m. This torque threshold was selected to prevent fast muscle fatigue buildup during the durations of the cycling trials. The selected pulse width for each participant was used during the cycling trials described below. For all cycling trials, the stimulation frequency and current amplitude of FES were fixed at 60 Hz and 80 mA, respectively, as done in other FES-cycling results [6].

At the beginning of each cycling trial, a passive torque test was performed where the electric motor passively rotated the rider’s legs [6] at a constant cadence of 60 RPM without FES to obtain an estimate of the rider’s passive torque. Thus, the active torque generated by the muscles was determined by subtracting the passive torque estimate from the real-time torque measurements. The FES-cycling trials with and without vibratory stimuli were conducted for 2 minutes with the electric motor tracking the target cadence using a robust sliding-mode controller. FES-cycling testing included two trials; one trial without vibration (i.e., typical FES-cycling) and another trial with vibration applied on the quadriceps bilaterally. Participants were instructed to avoid providing voluntary contribution during both cycling trials. FES-cycling was assisted by the electric motor to maintain a cadence of 60 RPM. Each cycling trial started with the electric motor passively bringing the rider to the target cadence for 25 seconds before applying FES and vibration (for the vibration trial). After reaching the desired cadence, FES was applied in open-loop fashion during all cycling trials only within kinematic efficient regions of the crank cycle for each participant [6]. Across all subjects, FES was applied within the interval of [66, 157] degrees. Vibration was applied concurrently with FES only. A period of 24-72 hours was enforced between the sessions for muscle recovery.

Data Analysis

For all trials, data collection started at the point at which the motor brought the rider to the target cadence. The active torque was computed and stored only during the crank angles where FES was applied (i.e., FES regions). A contraction is the average of the active torque of FES regions happening twice every cycle. The mean active torque for every contraction was averaged with a moving window of 1-second; it was then normalized by the maximum active torque produced during the trial for each participant. The normalized curves for all participants were combined and averaged. Three metrics to assess performance were compared across trials: mean active torque, fatigue time, and fatigue rate.

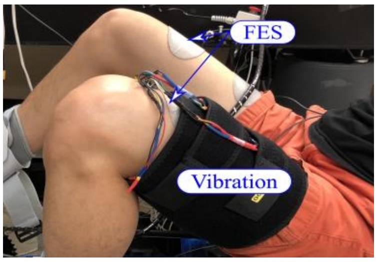

Figure 1. Participants seated in the cycle wearing a garment on both thighs (not depicted here for clarity), which contains the vibration motors. The pair of FES electrodes lie below the garment and are placed in the proximal and distal part of the quadriceps muscle group on both legs.

Fatigue time is the elapsed time between the maximum torque contraction and the contraction at which the torque decreased by 30% of the first contraction (measured in the number of contractions) [21]. Fatigue rate is the slope of the best fit linear curve of the function of torque output over 120 contractions. Fig. 2 depicts the normalized mean torque of all participants over the contractions displaying each activation of FES.

Results

The normalized active torque is shown in Fig. 2 as a function of contractions for the four participants during both cycling trials. Mean active torque, fatigue rate and fatigue times are presented for each participant (including the used pulse width) in Tab. 1 for the FES-cycling trials with and without vibration along with the first and third quartile (Q1 and Q3), respectively.

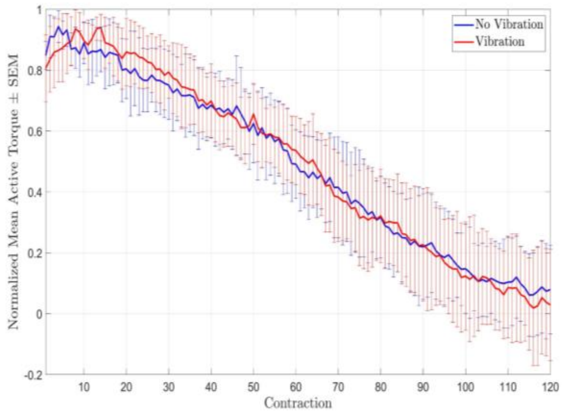

Figure 2. Each data point represents the mean value of the active torque over all participants. The maximum torque for each participant was achieved at a different number of contractions. SEM stands for the standard error of the mean.

Table 1: Mean active torque, fatigue time and fatigue rate for the FES-cycling trials with and without vibration across the four subjects. The pulse width used for each subject was kept constant for both cycling trials.

	mean active torque		**fatigue time**		**fatigue rate (10^-3)**	
Subject-Pulse Width	***no vib***	***vib***	***no vib***	***vib***	***no vib***	***vib***
S1-75	0.49	0.57	42	55	-9.4	-9.4
S2-80	0.45	0.39	41	41	-9.5	-11.3
S3-80	0.53	0.50	28	33	-5.8	-7.2
S4-90	0.57	0.53	35	33	-7.2	-6.3
Q1	**0.39**	**0.48**	**29.5**	**31.5**	**-9.4**	**-9.4**
Median	**0.44**	**0.51**	**43**	**37**	**-8.8**	**-7.0**
Q3	**0.56**	**0.55**	**52.5**	**52.5**	**-7.3**	**-6.2**

Discussion

Vibration stimuli applied to the tendon or muscle belly has been suggested to induce motor activation and modulate afferent inputs [17, 20]. Moreover, vibration targeting tendons has shown to attenuate spastic-like activity, which may aid to mitigate involuntary muscle spasms in people with SCI [22]. Vibration applied to the muscle belly of the quadriceps, hamstrings, and tensor fascia latae muscles has elicited step-like responses in individuals with SCI [22]. Prolonged vibrational stimuli over the rectus femoris for 10 minutes shows significant reduction in leg spasticity after SCI [23].

The motivation of the present work was to examine the influence of vibration during FES-cycling. The electric motor achieved satisfactory cadence tracking because there was a difference of 1.76% (p=0.44) of standard deviation of cadence between cycling with (0.172) and without (0.169) vibration for all trials. Hence, cadence was consistent during all cycling trials. There were no statistically significant differences of mean active torque between the cycling trials with and without vibration. The study only tested 4 healthy young subjects (e.g., data set was limited) and a rest period of 24-72 h was used to prevent muscle fatigue to influence the cycling trials. Hence, a potential different trend can be obtained with the recruitment of individuals with SCI and randomizing the order of the trials.

Fatigue rates were linearized for best fit (R^2= 0.98). The mean fatigue rate for all participants was 5.23% greater for the trial with vibration than the trial without vibration. However, fatigue rates highly varied across participants. The trial with vibration yielded 10.75% lower standard deviation of the active torque than the trial without vibration. This can be interpreted as vibration reducing the variance of active torque output compared to the no vibration trial. Along with the motivation of the present study to examine the influence of vibratory stimuli for adapting the muscle capacity to evoke active torque, previous studies have shown isometric torque increments during electrical stimulation coupled with vibratory stimuli. In [24], increased extra torques (generated by vibratory stimuli) were found to reach values up to 50% of the maximum voluntary contractions on top of the peripheral torque elicited by percutaneous electrical stimulation. Vibratory stimuli of 100 Hz for 2-second periods were applied to the Achilles tendon while alternating with electrical stimulation. However, some subjects exhibited no extra force produced by vibration.

Combining vibratory and electrical stimuli may provide neural adaptations and enhanced muscle performance, optimized by stimulation of sensory axons. Even though the present work also investigated the coupled scenario of vibration and electrical stimulation, there are differences compared to the study in [24]. First, in [24] the Achilles tendon was vibrated rather than the quadriceps muscle belly, which may cause a modified effect in the afferent input. The FES fatigue bouts, beyond using different frequencies, differed significantly in the stimulation duration, with a much longer duration for the present work. Experiments computed torque under isometric conditions while current experiments were performed pedaling on a bicycle. Finally, in [24] the authors may have been able to trigger a centrally mediated excitatory mechanism (in addition to the peripheral sensory activation) by applying vibration to the Achilles tendon; however, there is no evidence of such a mechanism in the present work.

The effectiveness of vibration stimuli may vary according to several neuromuscular factors. In this cycling paper, the vibratory stimulus was applied on the skin superficial to the quadriceps muscle belly at a low amplitude and relatively high frequency. Vibration motors are placed on the surface of the skin as compared to tendon vibration where the mechanical device physically taps against the tendon with a fixed magnitude. Stimuli with a frequency of 100 Hz have been shown to suppress muscle sensation [24]. Although this sensation suppression was not rigorously assessed during the cycling trials, several participants experienced a similar muscular output torque suppression sensation when vibration was applied concurrently with FES. Thus, after reaching a frequency threshold, vibration force suppression plateau. Therefore, motivation exists in future work to examine the influence of different vibration frequencies in FES-cycling.

Further evidence of torque facilitation or depression (i.e., increased or reduced torque) due to the effect of the vibratory stimuli during FES-cycling is to be obtained with a larger sample size. The effects of vibration on muscle fatigue and spasticity in individuals with SCI also remains to be investigated. Future work will also include modeling and analysis of the fatigue rates during cycling as in [25]. Exploring vibration to ease painful sensation for FES applications is also to be explored. The optimization of vibration and electrical stimulation parameters will be explored for different cycling cadences.

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