Influence of Vibration Stimuli on Neuromuscular Electrical Stimulation of the Quadriceps Femoris Muscle Group

Victor H. Duenas, Christian A. Cousin, Ryan J. Downey, Donald C. Bolser, and Warren E. Dixon

***Abstract*— Skeletal muscle fatigue and individual's tolerance threshold limit the effectiveness of the application of neuromuscular electrical stimulation (NMES) in rehabilitative settings. Researchers have focused on reducing muscle fatigue by developing different stimulation techniques (e.g., stimulation parameter modulation, doublets, and asynchronous stimulation). However, the early onset of NMES-induced fatigue continues to be a limiting factor. Mechanical vibration is potentially beneficial to alleviate pain and induce muscular activity; however, the combined effect of vibration and NMES is presently unclear. In this paper, vibratory stimuli are delivered over the skin surface (superficial to the quadriceps belly) to study its influence on the torque output during isometric NMES-evoked contractions.**

Index Terms- NMES, Vibratory Stimuli, Fatigue

I. Introduction

Neuromuscular electrical stimulation (NMES) has been used in rehabilitative procedures to preserve and recover muscle mass and functionality after neurological damage due to disease and injury or to treat muscle atrophy as a result motion impairment or immobilization [1-2]. Despite these promising results, skeletal muscle fatigue develops more rapidly during NMES than volitional contractions, limiting the effectiveness of NMES [3-4]. Researchers have studied electrical stimulation parameters to determine their impact on muscle fatigue. Increased stimulation frequencies are associated with increased fatigue rates [3-4], while pulse duration and intensity have a lesser effect on the rate of fatigue.

In different experimental settings, induced mechanical vibration has been suggested to be potentially beneficial to alleviate chronic pain [5], gain muscle power [6], induce muscular activity, improve lower limb kinematics, and enhance conventional resistance exercise gains [7-8]. Popular vibratory devices include vibratory bars or motor-vibration systems, custom-made vibration machines, e.g., designed for grip force testing or upper arm rehabilitation [7], and whole body vibration (WBV) platforms [8-9]. WBV is the most dominant modality of mechanical vibration for strength-training applications. Electromyographic (EMG) responses in the lower body have been recorded for different vibration frequencies inducing neuromuscular responses [9-10]. An increase in the root-mean-square (RMS) of the EMG (EMG_{RMS}) activity was observed in the vastus lateralis muscle of professional women volleyball players tested in a half-squat position on a vibration platform at 30 Hz compared to isometric conditions without vibration stimuli [8]. The increase in muscle activity (i.e., EMG_{RMS}) during WBV or other vibration treatments has been explained through muscle spindle-induced reflexive recruitment of inactive motor units [9-10]. 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 [11]. It has been suggested that strength gains while using vibration treatments may induce neural adaptations thus explaining improved muscle performance [11]. Muscle response to vibration depends on the mechanical stimuli localization, frequency, and amplitude. Vibratory stimulation has shown increased agonist and antagonist muscle activation, e.g., in the triceps brachii, dependent on the frequency of the vibrating bar-motor system [7]. This may provide a powerful alternative to obtain extended muscle activation in strength-training and low-force rehabilitation applications compared to high resistance exercise in the absence of vibration.

The aim of this work is to investigate the effect of vibratory stimuli applied to the quadriceps muscle belly while performing NMES. It is well accepted that mechanical vibration delivered primarily to the muscle tendon or muscle belly can elicit a tonic vibration reflex (TVR), resulting from the muscle spindle primary endings (Ia fibers) activity [11-12]. However, the study of motor control encompasses a complex relationship between the vibratory-induced contraction (TVR), muscle fatigue, and motor unit recruitment and synchronization [13]. In addition, the coupling of the vibratory stimulus with NMES will have an uncertain combined effect on the development of NMES-induced fatigue and the target muscle response. The objective of the present study is to determine if mechanical vibration might enhance or degrade active isometric torque output during electrically-elicited isometric contractions.

II. Methods

A. Subjects

Five healthy male subjects (aged 25.3 ± 4.2 years) participated in the study. Each participant gave written informed consent to enroll in the study, as approved by the institutional review board at the University of Florida. All the participants had prior experience with similar NMES protocols but not with the inclusion of the coupled vibratory stimulus.

B. Apparatus

The testing apparatus primarily consisted of a modified leg extension machine (LEM). The LEM has seating adjustments to align the axis of rotation of the participant's knee joint with the axis of rotation of the LEM. A force transducer was utilized to measure isometric knee-joint torque. Isometric torque was recorded during the electrical stimulation fatigue tests with and without the effect of the vibratory stimulus. A data acquisition device (Quanser QPIDe) was used with a personal computer executing MATLAB/Simulink for data logging.

Stimulation pulses were delivered by a current controlled functional 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

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quadriceps muscle group [surface electrodes for the study were provided compliments of Axelgaard Manufacturing Co., Ltd. (ValuTrode®, USA)]. The mechanical vibratory stimulus was applied to the quadriceps muscle belly using a custom-made adjustable leg sleeve designed to contain the vibration motors (Pico VibeTM, Precision Microdrives, United Kingdom). Each vibratory motor is nine millimeters in diameter and has a rated frequency of 230 Hz and vibration amplitude of 6g (g-force or acceleration of gravity) at a nominal 3V constant voltage. Twenty vibration motors were active when the vibratory stimuli was applied during the stimulation protocols. The garment was secured to the participant's thigh using Velcro straps to provide an appropriate fit thus having a good pressure between the vibratory motors and the skeletal muscle belly. The placement of the garment containing the vibratory motors and the electrodes is depicted in Fig. 1. The magnitude and frequency of the vibration of a single motor were characterized by attaching a small, low power tri-axial accelerometer (ADXL326, Analog Devices, USA) between the surface of the garment and one Velcro strap with the resulting measurements of ±2g-force (perpendicular axis) and 120 Hz.

C. Electrical Stimulation and Vibration Protocols

For all experiments, the stimulation frequency and current amplitude were fixed at 30 Hz and 90 mA, respectively. Biphasic symmetric rectangular pulses were used throughout. A single fatiguing session included a pretrial test and the main fatigue tests. During the pretrial test, the pulse width was adjusted to evoke an isometric torque output of 25 N·m without the influence of the vibratory stimuli. This desired initial torque output was targeted for each participant's legs by using 5-second stimulation pulse trains separated by 25 seconds of rest between pulse trains in order to avoid the buildup of fatigue prior to the actual fatigue test. The pulse duration was adjusted in real time during the resting periods until the torque magnitude reached 25 N·m. This value was attained by all the participants. During the pretrial test, the subjects had the opportunity to familiarize themselves with electrical stimulus and vibratory stimulus independently.

After the pretrial test, participants completed the fatigue test, which consisted of thirty NMES-evoked contractions (each 5 seconds long) using a 50% duty cycle (5 minutes total stimulation). The pulsewidth was modulated by applying a ramp-up for 1 second, a constant input for 3 seconds and a ramp-down for 1 second at each pulse train, similar to [14]. The effect of a constant amplitude and frequency vibration was investigated by delivering a constant 3V to the vibration motors. The NMES protocol was conducted with and without constant vibratory stimuli. Each fatiguing session consisted of a single experiment on each participant's leg. A minimum period of 48-96 hours was enforced between the sessions to achieve muscle recovery. The testing order of the vibration condition (no vibration versus constant vibration) was randomized for both legs. The mean pulse duration for all individuals was 102.7±44.1 µs.

D. Data Analysis

For all trials, the mean isometric torque was computed at each contraction over a window of the contraction plateau starting 500-milliseconds after the ramp-up input period and ending at the start of the ramp-down period (2.5-second window). The mean torque for every contraction was then normalized by the mean torque of the first contraction. As described in Section II.C, the same initial torque was targeted for all participants. The actual initial torque never exceeded a ± 10% range from the desired 25 N·m. Two metrics to assess muscle fatigue were compared across protocols: fatigue index and fatigue time.

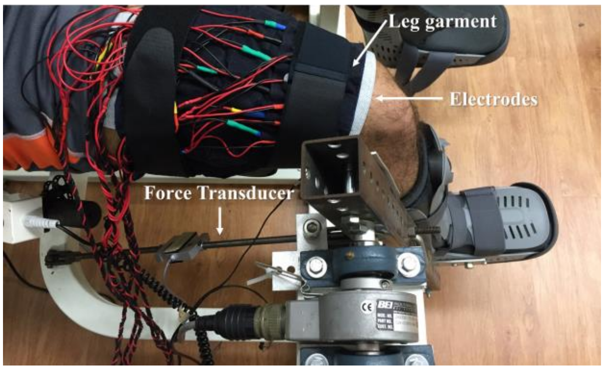

Figure 1. Participant seated in the LEM while wearing the garment, which contains the vibration motors. The pair of electrodes reside below the garment in the proximal and distal part of the quadriceps muscle group.

Fatigue index was quantified as the mean torque of the final three contractions divided by the mean torque of the first contraction. Fatigue time is the elapsed time between the first contraction and the contraction at which the torque decreased by 30% of the first contraction. A Wilcoxon signed-rank test was performed to compare the mean torque between the constant vibration and the no vibration protocols. The same nonparametric test was applied to determine significance of the two fatigue metrics. For all tests performed, statistical significance was set at $\alpha=0.05$.

III. RESULTS

The normalized isometric knee-joint torque at each contraction is shown in Fig. 2 as a function of contraction number. Fatigue times and fatigue indices are presented in Table I for the NMES protocol with and without constant vibration along with the first and third quartile (Q1 and Q3) respectively. The Wilcoxon signed-rank test revealed a significant difference in the mean isometric torque between both protocols across contractions ($p<0.001$). This implies that fatigue increased, (i.e., larger torque decay) in the presence of constant vibration. Regarding the two fatigue metrics, the Wilcoxon signed-rank test revealed no significance for the fatigue time, (i.e., there is not a significant difference on the fatigue onset) ($p=0.57$). In terms of fatigue index, no significant differences were detected between tests ($p=0.0645$); however, due to the small data set and the conservativeness of nonparametric tests, a potential trend can be further explored in future efforts.

TABLE I. CONSTANT VIBRATION VERSUS NO VIBRATION PROTOCOLS: FATIGUE INDEX AND FATIGUE TIME

	Fatigue Index		**Fatigue Time**	
Subject-Leg	***NO VIB***	***VIB***	***NO VIB***	***VIB***
S1-Left	0.683	0.601	140	130
S1-Right	0.426	0.333	40	80
S2-Left	0.708	0.609	300	170
S2-Right	0.519	0.460	130	80
S3-Left	0.662	0.667	220	270
S3-Right	0.542	0.452	130	70
S4-Left	0.743	0.754	300	300
S4-Right	0.662	0.662	250	260
S5-Left	0.670	0.677	220	220
S5-Right	0.658	0.511	70	80
Q1	**0.536**	**0.458**	**115**	**80**
Median	**0.662**	**0.610**	**220**	**170**
Q3	**0.698**	**0.674**	**287.5**	**267.5**

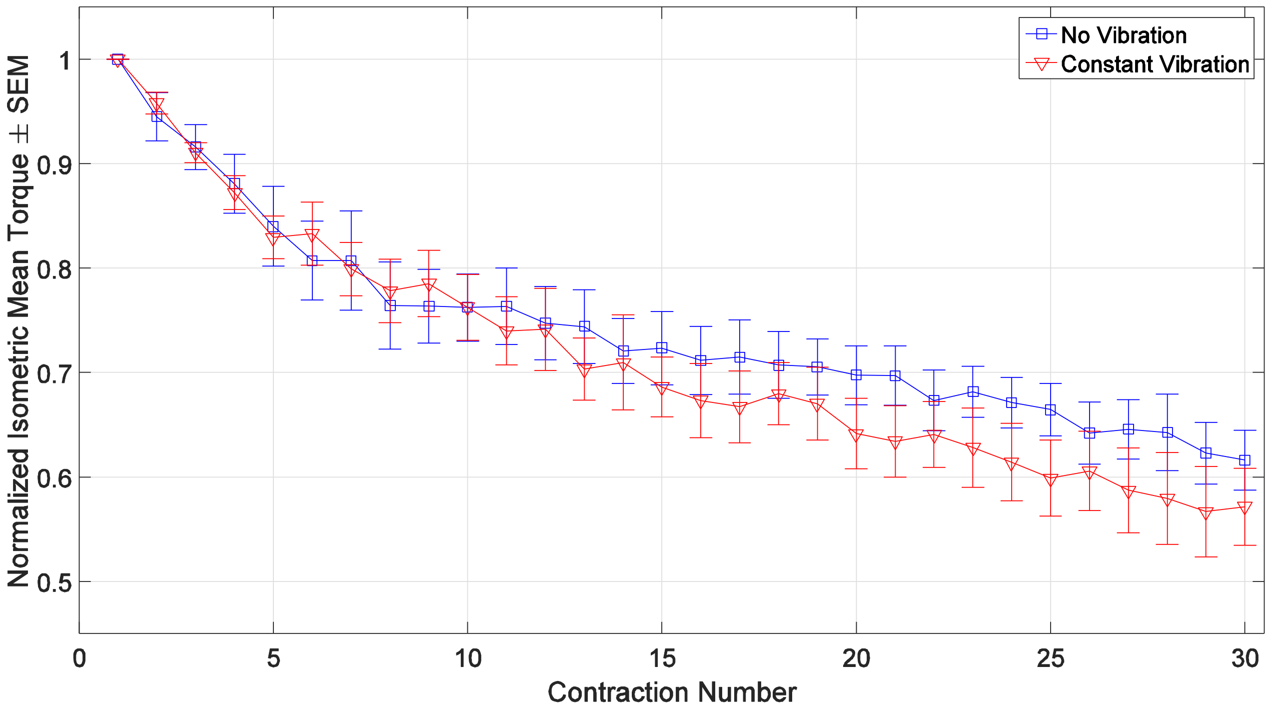

Figure 2. Mean normalized isometric torque ± the standard error of the mean (SEM) as a function of the contraction number. Each data point represents the mean value over all participants. On average (across all contractions) the torque was 2.705% greater for the no vibration protocol. The maximum torque difference was of 6.564% at contraction number 25.

IV. Discussion

Vibration applied to the muscle tendon or belly has been suggested to induce motor activation and modulate afferent inputs, which are strong stimuli for the activation of muscle spindle primary endings and mechanoreceptors [12, 15]. Constant vibration resulted in a statistically significant lower torque output on average across the thirty contractions among all participants. Although this lower torque output did not translate into a lower fatigue index for the constant vibration protocol, the data sample was relatively small and conservative nonparametric tests were used to determine statistical significance. Moreover, as depicted in Fig. 2 and evidenced by the Wilcoxon test on fatigue time (p=0.57), it appears that the effects of vibration (specifically, suppressing the torque output) occurs later in the trial. The primary motivation of the present work was to determine if the applied vibration could enhance torque output (e.g., indirectly via afferent sensory pathways or by directly recruiting additional motor units). Interestingly, for some participants, a period during the first 10 contractions resulted in larger torque output (not statistically significant) compared to the non-vibratory protocol. A similar torque output facilitation behavior was reported for vibration applied to the ankle dorsiflexor muscle tendon resulting in enhanced contraction force and EMG activity [16]. However in the present work, the prolonged effect of constant vibration across the full stimulation period resulted in a markedly induced suppression of the output torque. The authors in [16] explained this decline in muscle contraction force by a combined decline in the motor unit firing rates during sustained maximum voluntary contractions (MVC) and by changes in afferent inflow from the contracting muscle reducing the amount of excitation received by the α-motoneurons. However, subject variability plays a determinant factor to assess vibration-induced reduction of contraction force.

Although the present study did not yield higher isometric torque, previous studies have shown isometric torque increments during electrical stimulation coupled with vibratory stimuli. In [17] increased extra torques (generated by vibratory stimuli) were observed that reached values up to 50% MVC 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. The combination of the 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 [17]. First, in [17] the Achilles tendon was vibrated rather than the quadriceps muscle belly, which may cause a modified effect in the afferent input. The NMES fatigue bouts, beyond using different frequency, differed significantly in the stimulation duration, with a much longer duration for the present work. Finally, in [17] 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, but there is no evidence of such a mechanism in the present work.

Force suppression in response to vibration stimuli has been previously reported. In [13], fatigue was greater when vibration was applied during sustained grip exertion resulting in increased fatigue and recovery time. The largest decrease in twitch force occurred after a task under sustained vibration as compared to the intermittent vibration trials [13]. This outcome may suggest a modified motor unit recruitment pattern during vibration, where a derecruitment effect of high-threshold motor units in vibration has been previously shown [6]. Based on the results in the present work, the generalized suppression of output force by the application of constant vibration may cause a double recruiting effect of motor units by both NMES and the vibratory stimuli which exacerbates the effect of fatigue after a certain initial period during the vibration protocol. Alternatively, force suppression has been explained in [16] by the incapacity to generate or maintain high firing rates in high-threshold motor units during MVCs in man.

The effectiveness of the vibration treatment may vary according to several biomechanical and peripheral factors in the muscle. In the present study, the vibratory stimulus was applied on the skin superficial to the quadriceps muscle belly at a low amplitude and relatively high frequency. There is no definitive evidence that the delivered vibratory stimuli stimulated muscle spindles, since the vibratory motors were placed on the skin as compared to tendon vibration where the vibrator is pushed into the skin at suprathreshold intensities. High frequencies have been shown to suppress sensation or sensation-induced muscle activity [18]. Although this sensation suppression was not parametrized in the current work, it is expected that some participants experienced a similar muscular output torque suppression sensation. That is, after reaching a frequency threshold, vibration force suppression plateaus (maximum force decay is reached). Conversely, low frequency has been found to be insignificant when developing knee extensions and it is ignored by the sensory system [19]. This outcome may imply that there is a lower frequency threshold where a total rejection of the vibratory stimuli takes place and an upper frequency threshold where torque output sensation suppression may take place. It has been also suggested that vibration may be more effective if it is brief or intense in order to produce a synchronous afferent flow [15]. This clearly motivates studies on modulating the activation of the vibratory stimuli, i.e., determine predefined on/off times throughout the NMES.

The effects of vibration on pain sensation and how this may relate to the output torque suppression found in the present work remains to be studied. It is yet to be determined if there is a correlation between vibratory stimuli and pain feedback. Contrary to what was initially expected, no overall torque facilitation (i.e., increased isometric torque) can be concluded by the effect of the vibratory stimuli. The optimization of vibration stimulation parameters may require a concomitant revision of the NMES parameters utilized in the present study.

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