Interleaved Neuromuscular Electrical Stimulation of the Paralyzed Plantarflexors

Austin J. Bergquist, Matheus J. Wiest, Yoshino Okuma, David F. Collins

***Abstract*— Objective: Neuromuscular electrical stimulation (NMES) over a muscle belly (mNMES) recruits superficial motor units (MUs) preferentially, while NMES over a nerve trunk (nNMES) can recruit MUs deep within a muscle. Presently, we characterize the feasibility of "interleaving" pulses between the mNMES and nNMES sites (iNMES) to reduce fatigue (torque-decline) in people who experience paralysis due to chronic spinal cord injury. Methods: Plantarflexion torque and soleus electromyography were recorded from 8 participants. A fatigue protocol (intermittent 20-Hz trains; 2-s-on-2-s-off for 5-min; 75 contractions) was delivered using iNMES. Results: Torque declined by ~54%, while M-waves were consistent, from the beginning to the end of the 5-min fatigue protocol. Discussion: The present data demonstrate that iNMES may represent a method of delivering NMES that minimizes the effect of neuromuscular propagation failure, or high-frequency-fatigue, on torque-decline.**

I. Introduction

Neuromuscular electrical stimulation (NMES) can be delivered over a muscle belly (mNMES) or nerve trunk (nNMES). However, both methods of NMES are limited by rapid fatigue, characterized by excessive torque-decline. Such torque-decline is due, in part, to the high motor unit (MU) discharge frequencies associated with NMES, which can lead to neuromuscular propagation failure (i.e. high-frequency-fatigue; HFF), as demonstrated by a decline in the M-wave amplitude recorded in the EMG signal. Determining ways of delivering NMES in ways that reduce MU discharge frequencies, but that maintain high torque output, holds promise for reducing torque-decline during NMES-based rehabilitation.

When mNMES is delivered to produce small to moderate contractions, superficial MUs are activated preferentially due to their close proximity to mNMES electrodes.(1-5) This leaves MUs located deep in a muscle relatively inactive. However, during nNMES, the depolarization of motor axons recruits both superficial and deep MUs within a muscle, regardless of NMES intensity.(5) With this in mind, we developed a method of NMES whereby pulses are "interleaved", or alternated, between mNMES and nNMES (iNMES), the aim of which is to reduce the high frequencies at which MUs discharge during NMES, by exploiting the above mentioned differences in the spatial distribution of MUs recruited by mNMES and nNMES. During NMES of healthy dorsiflexors, iNMES reduced torque-decline by 28% and 19% compared with mNMES or nNMES, respectively.(6)

The objective of this preliminary study was to characterize the feasibility of delivering iNMES to minimize torque-decline for people who experience paralysis due to chronic spinal cord injury (SCI), in whom NMES-rehabilitation is common practice. Previously, we compared the fatigability of contractions during mNMES and nNMES of the ankle plantarflexors in 8 participants with SCI.(7) The present data represent the first report of iNMES in the plantarflexors, and in people with SCI.

II. Methods

The present methods are identical to those reported previously (7). In brief, 8 participants with chronic SCI volunteered for a 3rd session involving iNMES, 3-4 months after their initial 2 sessions. All procedures were approved by the Health Research Ethics Board at the University of Alberta. Plantarflexion torque, soleus motor (M-) waves and Hoffmann (H-) reflexes were recorded during a fatigue protocol (intermittent 20-Hz trains; 2-s-on-2-s-off for 5-min; 75 contractions). Relative changes in torque and M-wave amplitudes, from the beginning (mean of initial 5 contractions) to the end (mean of last 5 contractions) of the fatigue protocol, were also calculated. Deviations from previous methods (7) include the type of NMES, how the NMES intensity was set and statistical analyses, as reported below.

A. iNMES

iNMES was delivered using 2 constant-current stimulators (200-μs pulse duration; DS7AH and DS7A Digitimer, Welwyn Garden City, UK). Electrodes were placed over the triceps surae muscles (mNMES) and tibial nerve trunk (nNMES), as done previously (7). iNMES was achieved by alternating every other NMES pulse between the mNMES ($iNMES_{(m)}$) and nNMES ($iNMES_{(n)}$) sites, with each site generating separate M-waves. Fig. 1A shows representative electromyographic (EMG) traces during the iNMES fatigue protocol. Each site was stimulated at 10-Hz with a phase shift of 180° with respect to the other, giving a composite iNMES frequency of 20 Hz delivered to the plantarflexors as a whole.

B. Setting the NMES Intensity

To set the NMES intensity for the fatigue protocol, 2-s trains of 10-Hz NMES were delivered while the intensity was adjusted until peak torque was equivalent to ~50% peak twitch torque. This was done independently for both the $iNMES_{(m)}$ and $iNMES_{(n)}$ sites. Interleaving pulses between the $iNMES_{(m)}$ and $iNMES_{(n)}$ sites at these intensities generated ~100% of peak twitch torque in each participant, which equates to ~27% of maximum tetanic torque at 40 Hz (8).

* This work was supported by an Alberta Paraplegic Foundation PhD Studentship (A.J.B.), a University of Alberta PhD Dissertation Scholarship (A.J.B.), a University of Alberta PhD Recruitment Scholarship (M.J.W.), a Science without Boarders Scholarship - CNPq (M.J.W.), the University of Alberta Centre for Neuroscience (Y.O.), and a Natural Sciences and Engineering Council of Canada Discovery Grant (D.F.C).

A.J. Bergquist (corresponding author) is with the Toronto Rehabilitation Institute – University Health Network, Toronto, Canada (phone: 416-597-3422 x5295; email: austin.bergquist@uhn.ca). M.J. Wiest, Y. Okuma and D.F. Collins are with the University of Alberta, Edmonton, Canada.

B. Statistics

Single group t-tests were used to test the relative changes in torque and M-wave amplitudes from the first 5 to the last 5 contractions of the fatigue protocol. Significance was set at $P<0.05$. Data are reported as mean ± standard error.

III. RESULTS

Torque declined significantly during the iNMES fatigue protocol [dagger †; $P < 0.01$; Fig. 1B], while M-waves did not change ($iNMES_{(m)}$: $P = 0.2$; $iNMES_{(n)}$: $P = 0.5$; Fig. 1C).

H-reflexes were evoked in 4 of 8 participants, consistent with previous sessions (7). However, the presence of H-reflexes during iNMES did not influence changes in torque (%initial; with H-reflexes: 49.7 ± 8.8, n=4; without H-reflexes: 42.6 ± 7.3, n = 4; unpaired t-test, $P = 0.53$), as it did previously for nNMES (7). Thus, H-reflex data are not discussed.

IV. DISCUSSION

Torque-decline during NMES is due, in part, to high MU discharge frequencies, which can lead to neuromuscular propagation failure (i.e. HFF), as demonstrated by a decline in the M-wave amplitude recorded in the EMG signal. Of note, fast MUs are more susceptible to HFF.(9) Consequently, HFF plays a prominent role during NMES-evoked contractions in people who experience chronic SCI (7, 11), in whom disuse leads to transformation of MUs from slow to fast.

Although torque declined significantly during iNMES, M-waves did not change at either site ($iNMES_{(m)}$, $iNMES_{(n)}$), indicating that HFF did not contribute to torque-decline during iNMES, consistent with iNMES of the dorsiflexors (6). Interestingly, the observed torque-decline during iNMES (~54%) is consistent with that observed previously in the same 8 participants (7) during nNMES (~55%), but less than during mNMES (~72%). Importantly, HHF contributed to much of the torque-decline observed previously (7), particularly during mNMES. In line with our rationale for developing iNMES, iNMES may represent a method of delivering NMES that minimizes the effect of HHF on torque-decline by minimizing the MU discharge frequencies typically associated with NMES by exploiting differences in the spatial distribution of MUs recruited by the $iNMES_{(m)}$ and $iNMES_{(n)}$ sites. If the unique technical challenges associated with iNMES (6) can be overcome, we would recommend iNMES over mNMES of the paralyzed plantarflexors, but also over nNMES of the paralyzed plantarflexors, as its performance was less affected by the presence of H-reflexes (7). Future work and further statistical analyses are required to confirm these conclusions.

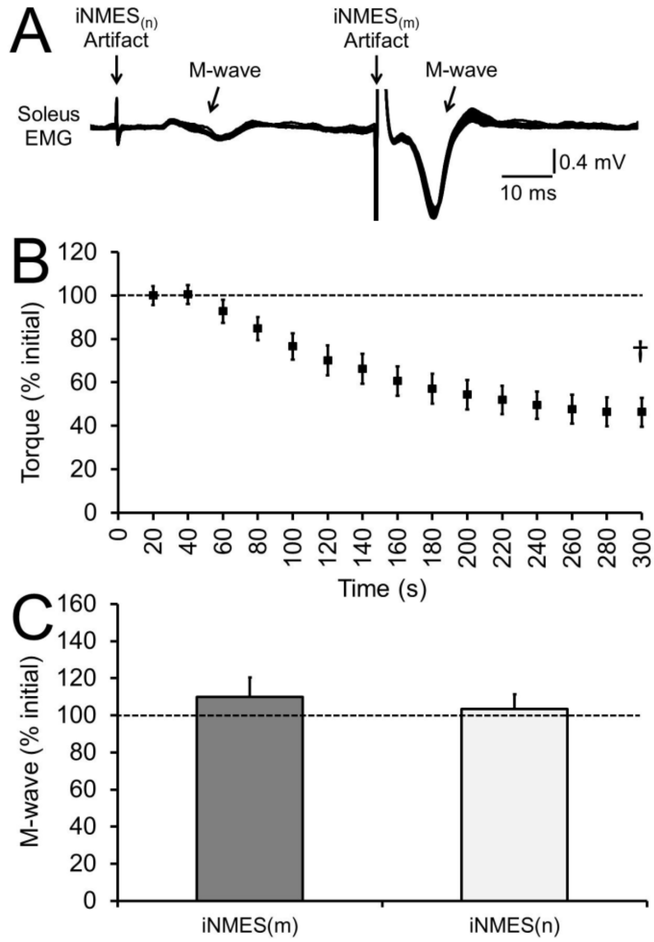

Figure 1. (A) Soleus EMG recorded from a single participant during the last contraction of the iNMES fatigue protocol. The EMG show 2 successive pulses; 1st pulse delivered to the $iNMES_{(n)}$ site, 2nd pulse delivered to the $iNMES_{(m)}$ site. Twenty of these EMG traces are overlaid, which include all 40 pulses of the 2-s, 20 Hz, iNMES contraction. (B) Torque during the 5 min fatigue protocol (n = 8). Each symbol represents data averaged over 20 s (5 consecutive contractions). The dagger (†) represents a significant difference from the last 5 contractions of the fatigue protocol to the initial (i.e. 100; horizontally dashed line). (C) Relative changes in M-wave amplitudes from the beginning to the end of the fatigue protocol. Shown are the mean amplitudes recorded during the last 5 contractions of the fatigue protocol, expressed as a percent of the mean of the initial 5 contractions. Error bars represent 1 standard error.

ACKNOWLEDGMENT

The authors thank Mr. Alejandro Ley for his technical support.

REFERENCES

[1] M. Vanderthommen, J.C. Depresseux, L. Dauchat, C. Degueldre, J.L. Croisie and J.M. Crielaard, "Spatial distribution of blood flow in electrically stimulated human muscle: a positron emission tomography study," *Muscle Nerve*, vol. 23, pp. 482-489, 2000.

[2] D. Boerio, M. Jubeau, R. Zory and N.A. Maffiuletti, "Central and peripheral fatigue after electrostimulation-induced resistance exercise," *Med Sci Sports Exerc*, vol. 37, pp. 973-978, 2005.

[3] L. Mesin, E. Merlo, R. Merletti and C. Orizio. "Investigation of motor unit recruitment during stimulated contractions of tibialis anterior muscle," *J Electromyogr Kinesiol*, vol. 20, pp. 580-589, 2010.

[4] N. Place, N. Casartelli, J.F. Glatthorn and N.A. Maffiuletti. "Comparison of quadriceps inactivation between nerve and muscle stimulation," *Muscle Nerve*, vol. 42, pp. 894-900, 2010.

[5] Y. Okuma, A.J. Bergquist, M. Hong, K.M. Chan and D.F. Collins. "Electrical stimulation site influences the spatial distribution of motor units recruited in tibialis anterior," *Clin Neurophysiol*, vol. 124, pp. 2257-2263, 2013.

[6] J.W.H. Lou, A.J. Bergquist, A. Aldayel, J. Czitron and D.F. Collins, "Interleaved neuromuscular electrical stimulation reduces fatigue," *Muscle Nerve*, in revision for publication.

[7] A.J. Bergquist, M.J Wiest, Y. Okuma and D.F. Collins, "H-reflexes reduce fatigue of evoked contractions after spinal cord injury," *Muscle Nerve*, vol. 50, pp. 224-234, 2014.

[8] R.K. Shields and Y.J. Chang, "The effects of fatigue on the torque-frequency curve of the human paralysed soleus muscle," *J Electromyogr Kinesiol*, vol. 7, pp. 3-13, 1997.

[9] R.M. Enoka, N. Trayanova, Y. Laouris, L. Bevan, R.M. Reinking and D.G Stuart, "Fatigue-related changes in motor unit action potentials of adult cats," *Muscle Nerve*, vol. 15, pp. 138-150, 1992.

[10] R.K. Shields, Y.J. Chang and M. Ross, "Neuromuscular propagation after fatiguing contractions of the paralyzed soleus muscle in humans," *Muscle Nerve*, vol. 21, pp. 776-787, 1998.