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Spatially Distributed Sequential Stimulation Reduces Muscle Fatigue during Neuromuscular Electrical Stimulation*

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***Abstract*—A critical limitation with neuromuscular electrical stimulation (NMES) approach is the rapid onset of muscle fatigue during repeated contractions, which results in the muscle force decay and slowing of muscle contractile properties. In our previous study, we demonstrated that spatially distributed sequential stimulation (SDSS) show a drastically greater fatigue-reducing ability compared to a conventional, single active electrode stimulation (SES) with an individual with spinal cord injury when applied for plantar flexors. The purpose of the present study is to explore the fatigue-reducing ability of SDSS for major lower limb muscle groups in the able-bodied population as well as individuals with spinal cord injury (SCI). SDSS was delivered through four active electrodes applied to the muscle of interest, sending a stimulation pulse to each electrode one after another with 90° phase shift between successive electrodes. For comparison, SES was delivered through one active electrode. For both modes of stimulation, the resultant frequency to the muscle as a whole was 40 Hz. Using corresponding protocols for the fatiguing stimulation, we demonstrated the fatigue-reducing ability of SDSS by higher fatigue indices as compared with single active electrode setup for major leg muscles in both subject groups. The present work verifies and extends reported findings on the effectiveness of using spatially distributed sequential stimulation in the leg muscles to reduce muscle fatigue. Application of this technique can improve the usefulness of NMES during functional movements in the clinical setup.**

I. Introduction

Neuromuscular electrical stimulation (NMES) is used to promote physiological and functional improvement in paralysed limbs [1, 2] and counteract musculoskeletal atrophy [3, 4]. However, while it has succeeded in assisting individuals with neuromuscular disorders, a critical limitation with this rehabilitative approach is the rapid onset of muscle fatigue during repeated contractions [5], which results in the muscle force decay and slowing of muscle contractile properties [6].

The increased fatigability with NMES is thought by some researchers to reflect a reversal of the size principle of recruitment [7], when larger axons that innervate the more easily fatigable fibers are recruited at low stimulus magnitudes, and the smaller axons follow with increased stimulation levels [1, 5]. Another plausible explanation is that, while during voluntary contraction, the work is being shared between different motor units of the same muscle [5], conventional NMES does not permit alterations in recruitment of motor units because all parameters remain fixed during the bout [5].

One of the means to counter force loss during electrical stimulation is aimed at achieving an asynchronous behavior by delivering electrical stimulation through multiple electrode locations on a single site, producing a fused contraction with relatively low stimulation rates, and delaying the onset of fatigue. This type of spatially distributed and sequentially applied stimulation is referred to as 'sequential stimulation'. Fatigue was reduced with such stimulation, widely shown in animal experimental models [8-11]. Until now, only a few studies [12-16] investigated this stimulation method in human experimental setups, however, this method has not been successfully incorporated into clinical applications.

In our previous study [13], we demonstrated that spatially distributed sequential stimulation (SDSS) show a drastically greater fatigue-reducing ability compared to a single active electrode stimulation (SES) with an individual with spinal cord injury (SCI) when applied for plantar flexors. The purpose of the present study is to explore the fatigue-reducing ability of SDSS for major lower limb muscle groups in SCI populations.

II. Methods

A. Participants

Ten individuals with SCI (male, C5-T11, AIS A and B) participated in the study. All procedures were approved by the institutional review board at the Toronto Rehabilitation Institute and informed consent was obtained from each participant.

B. Devices and Measures

During the experiments, the Biodex Isokinetic Dynamometer (Biodex Medical Inc., Shirley, NY, USA) was used to measure the produced torque during the electrical stimulation of the (1) right knee extensors and (2) flexors, (3) plantar flexor, and (4) dorsiflexor muscles in isometric conditions.

A programmable 4-channel neuromuscular electrical stimulator (Compex Motion, Compex SA, Switzerland) was used to deliver transcutaneous electrical stimulation to the

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muscles of interest. Two modes of stimulation were compared: SDSS and SES (Fig. 1):

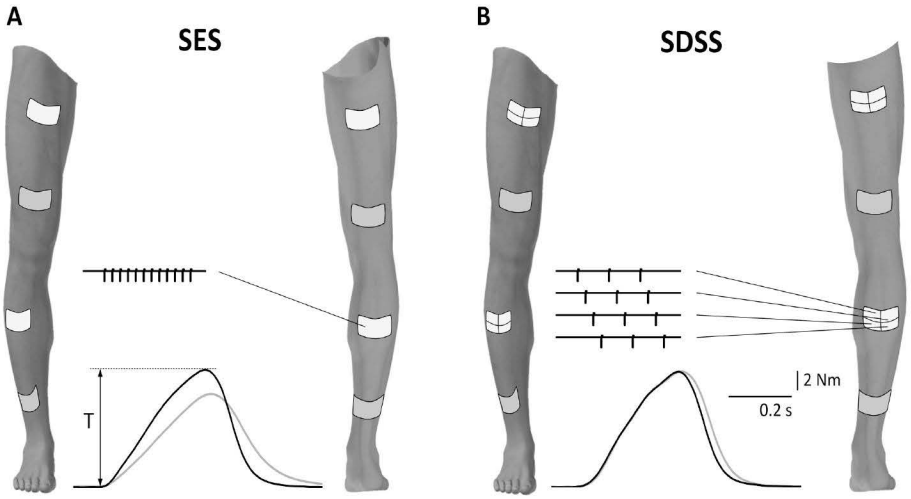

Figure 1. Schematic representation of SES (A) and SDSS (B). Electrode placements over the knee flexor and plantar flexor muscles for SES are shown on the left, while those for SDSS are shown on the right. Stimulation pulse shapes and timing are shown in the middle. Lower panel: Representative example of torque before (black lines) and after (gray lines) fatiguing stimulation using SES (left) and SDSS (right). T: torque amplitude.

- during SES, pulses were delivered conventionally through one active electrode at 40 Hz. Both active and reference electrodes were of 9 cm by 5 cm (Fig. 1A);
- during SDSS, pulses were sequentially distributed among the arrayed active electrodes. One 9 cm by 5 cm electrode was used as a reference electrode in the same location as during SES, and four 4.5 cm by 2.5 cm (in case of the dorsiflexors, the electrodes size was 2.5 cm by 2.5 cm) electrodes were placed so that together they covered exactly the same area as the active electrode during SES. Stimulation was delivered by sending a stimulation pulse to each of the four electrodes, one after another. Individual electrodes were being stimulated at 10 Hz with a phase shift of 90° between successive electrodes, giving a resultant stimulation frequency of 40 Hz as a whole (Fig. 1B).

The stimulation current had a rectangular, biphasic, monopolar pulse waveform with a pulse duration of 300 μs. The stimulator was programmed to deliver a bout of fatiguing stimulation consisted of 120 trains each of 12 pulses. The amplitude of the stimulation was adjusted to achieve the initial torque at the level about 8-12 Nm. The stimulation amplitudes were increased simultaneously for all SDSS electrodes, and didn't differ significantly from the amplitude during SES. SES and SDSS tests were conducted on a different day with at least 1 day of rest in between.

To indicate muscle force decay during the fatiguing stimulation, we calculated the fatigue index (FI) defined as the torque at the end of the 2-min stimulation normalized to the maximum torque [13].

C. Statistics

T-test comparisons were made to decompose significant effects after the fatiguing stimulation session for each outcome measures and for each group ($\alpha = 0.05$).

III. Results

An example of the torque time curves at the beginning (train 5) and at the end (train 115) of the fatiguing stimulation during SES and SDSS protocols appears in Fig. 1 (lower panel). A simple visual inspection of the figure suggests that the participant's performance, as represented by the torque peaks, maintained better using SDSS than using SES.

Fig. 2 displays the pooled effect of the fatiguing stimulation on the FI values during SES and SDSS for each muscle group. The paired t-tests indicated that the fatigue indexes were significantly larger in SDSS than in SES for knee extension ($p = 0.018$), knee flexion ($p = 0.020$), and plantarflexion ($p = 0.004$), while there was no significant difference between SDSS and SES for dorsiflexion ($p = 0.082$).

IV. Discussion

We investigated the effectiveness of spatially distributed sequential stimulation in reducing muscle fatigue during electrical stimulation in SCI population for major leg muscle groups. We demonstrate higher fatigue resistance during SDSS compared to the conventional SES approach. We suggest interleaved sequential stimulation to be used to reduce the negative effects of muscle fatigue during neuromuscular electrical stimulation. It has been shown in numerous studies that the higher and longer amount of the "therapeutic dose" of stress applied to the paralyzed tissue,

the greater success in the treatment of muscle atrophy [17, 18], as well as in functional outcomes and clinical/physiological improvements [17].

The analysis of the torque-time curve demonstrated that during the muscle contraction, the peak torque rapidly decreased in response to the stimulation and remained depressed for the duration of the test during SES. The FI

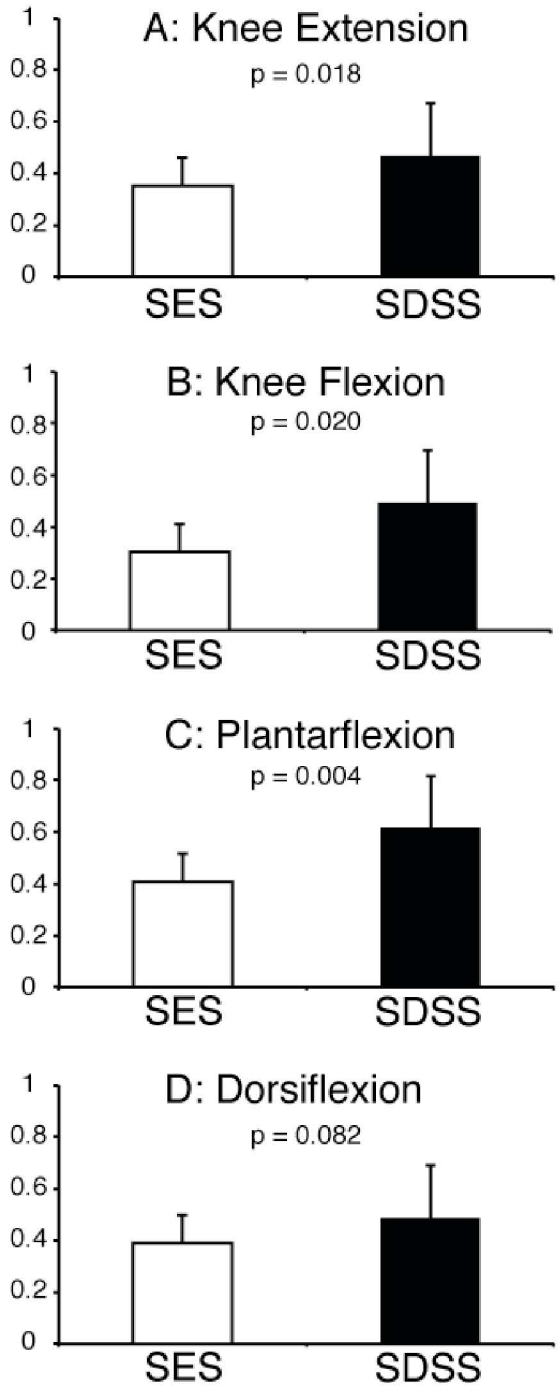

Figure 2. Fatigue index (FI) during SES (white column) and SDSS (black column) applied to knee extensors (A), knee flexors (B), plantar flexor (C), and dorsiflexor (D) muscles.

responded differently during SES and SDSS protocols demonstrating low fatigue resistance during SDSS, except for dorsiflexors. These findings indicate that a combination of higher torque-producing capacity and reduced fatigability during SDSS enabled it to perform a greater magnitude of contractile work during repetitive activation when compared with SES, for knee extensors and flexors, as well as for plantarflexors. The FI for dorsiflexors was larger with SDSS compared to SDS, while there was no statistical significance. Because the percentage of change in dorsiflexor was not very different from other muscle groups (33, 62, 51, 25 % for knee extensors, knee flexors, plantarflexors, and dorsiflexors, respectively), the p-value of the corresponding t-test ($p = 0.082$) was close to the significance level, and the number of subjects who did not show increments of FI for dorsiflexor was not much different from the other muscle groups (two, zero, one, two subjects for knee extensors, knee flexors, plantarflexors, and dorsiflexors, respectively), we think that when we increase the number of subjects, we will obtain the statistical difference for dorsiflexor as well.

The advantage of sequential stimulation in reducing muscle fatigue during NMES has been widely shown in animal experimental models [8-10], while a few attempts were made previously to reduce the muscle fatigue using the distributed sequential stimulation in human experimental setups [12, 14]. In [11] and [13], the target muscle group was knee extensors, and the electrodes were located widely over the knee extensors. However, in our previous [12] and the current study, we used the same electrode location between SDSS and SES, i.e., we simply divided the cathode electrode into 4 pieces. Thus, our method can be applicable for small single muscles such as finger/wrist flexors or extensors, which the method in [11] or [13] seem is not applicable to. As such, application of our method in single muscles or in arm muscle groups can be feasible and is a subject of further research. In addition, since the most of clinically relevant tasks are dynamic in nature, the effectiveness of SDSS during these tasks should be investigated in future.

V. Conclusion

Using corresponding protocols for the fatiguing stimulation, the present study demonstrated the fatigue-reducing ability of SDSS in SCI population by higher fatigue indices as compared with single active electrode setup. Thus, the present work verifies and extends reported findings on the effectiveness of using spatially distributed sequential stimulation in the leg muscles to reduce muscle fatigue. Application of this technique can improve the usefulness of NMES during functional movements in the clinical setup.

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REFERENCES

[1] L. R. Sheffler and J. Chae, "Neuromuscular electrical stimulation in neurorehabilitation," *Muscle Nerve,* vol. 35, pp. 562-90, May 2007.

[2] P. H. Peckham and J. S. Knutson, "Functional electrical stimulation for neuromuscular applications," *Annu Rev Biomed Eng,* vol. 7, pp. 327-60, 2005.

[3] A. J. Bergquist, J. M. Clair, O. Lagerquist, C. S. Mang, Y. Okuma, and D. F. Collins, "Neuromuscular electrical stimulation: implications of the electrically evoked sensory volley," *Eur J Appl Physiol,* vol. 111, pp. 2409-26, Oct 2011.

[4] S. Dudley-Javoroski and R. K. Shields, "Muscle and bone plasticity after spinal cord injury: review of adaptations to disuse and to electrical muscle stimulation," *J Rehabil Res Dev,* vol. 45, pp. 283-96, 2008.

[5] C. S. Bickel, C. M. Gregory, and J. C. Dean, "Motor unit recruitment during neuromuscular electrical stimulation: a critical appraisal," *Eur J Appl Physiol,* vol. 111, pp. 2399-407, Oct 2011.

[6] D. A. Jones, "Changes in the force-velocity relationship of fatigued muscle: implications for power production and possible causes," *J Physiol,* vol. 588, pp. 2977-86, Aug 15 2010.

[7] [E. Henneman, G. Somjen, and D. O. Carpenter, "Excitability and inhibitability of motoneurons of different sizes," *J Neurophysiol,* vol. 28, pp. 599-620, May 1965.

[8] H. K. Lau, J. Liu, B. P. Pereira, V. P. Kumar, and R. W. Pho, "Fatigue reduction by sequential stimulation of multiple motor points in a muscle," *Clin Orthop Relat Res,* pp. 251-8, Dec 1995.

[9] E. D. Zonnevijlle, N. N. Somia, R. W. Stremel, C. J. Maldonado, P. M. Werker, M. Kon, and J. H. Barker, "Sequential segmental neuromuscular stimulation: an effective approach to enhance fatigue resistance," *Plast Reconstr Surg,* vol. 105, pp. 667-73, Feb 2000.

[10] B. Lau, L. Guevremont, and V. K. Mushahwar, "Strategies for generating prolonged functional standing using intramuscular stimulation or intraspinal microstimulation," *IEEE Trans Neural Syst Rehabil Eng,* vol. 15, pp. 273-85, Jun 2007.

[11] K. Yoshida and K. Horch, "Reduced fatigue in electrically stimulated muscle using dual channel intrafascicular electrodes with interleaved stimulation," *Ann Biomed Eng,* vol. 21, pp. 709-14, Nov-Dec 1993.

[12] N. M. Malesevic, L. Z. Popovic, L. Schwirtlich, and D. B. Popovic, "Distributed low-frequency functional electrical stimulation delays muscle fatigue compared to conventional stimulation," *Muscle Nerve,* vol. 42, pp. 556-62, Oct 2010.

[13] R. Nguyen, K. Masani, S. Micera, M. Morari, and M. R. Popovic, "Spatially distributed sequential stimulation reduces fatigue in paralyzed triceps surae muscles: a case study," *Artif Organs,* vol. 35, pp. 1174-80, Dec 2011.

[14] L. Z. Popovic and N. M. Malesevic, "Muscle fatigue of quadriceps in paraplegics: comparison between single vs. multi-pad electrode surface stimulation," *Conf Proc IEEE Eng Med Biol Soc,* vol. 2009, pp. 6785-8, 2009.

[15] D. Graupe, P. Suliga, C. Prudian, and K. H. Kohn, "Stochastically-modulated stimulation to slow down muscle fatigue at stimulated sites in paraplegics using functional electrical stimulation for leg extension," *Neurol Res,* vol. 22, pp. 703-4, Oct 2000.

[16] W. W. Glenn, W. G. Holcomb, R. K. Shaw, J. F. Hogan, and K. R. Holschuh, "Long-term ventilatory support by diaphragm pacing in quadriplegia," *Ann Surg,* vol. 183, pp. 566-77, May 1976.

[17] R. K. Shields and S. Dudley-Javoroski, "Musculoskeletal plasticity after acute spinal cord injury: effects of long-term neuromuscular electrical stimulation training," *J Neurophysiol,* vol. 95, pp. 2380-90, Apr 2006.

[18] R. M. Enoka, *Neuromechanics of human movement*, 3rd ed. Champaign, IL: Human Kinetics, 2002.