Functional output performance in paraplegic cycling propelled by leg stimulation with middle frequency alternating current

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Abstract

Objective: To compare the functional outcome of electrical stimulation (FES) propelled cycling (evoked isometric force and work) when using modulated middle frequency alternating current (MFAC) or standard low frequency rectangular pulses (LFRP).
Methods: Eleven healthy subjects with complete spinal cord injury (SCI) volunteered.
Interventions: To evaluate cycling-relevant differences between LFRP and modulated MFAC stimulation, participants were exposed to isometric measurements and cycling experiments, performed during both 20 Hz LFRP and 4 KHz modulated with 50 Hz MFAC. Maximal isometric pedaling torque and dynamic work during 20 minutes of ergometer cycling were recorded for each of the two conditions.
Results: Isometric torque elicited during MFAC stimulation was significantly lower and pedaling work generated was highly and significantly lower than during standard LFRP.
Conclusion: The findings suggest that stimulated cycling of SCI subjects with low frequency is generally more effective than with modulated middle frequency alternating current in terms of torque and work.

1. INTRODUCTION

One requirement for applying FES in complete and incomplete spinal cord injury (SCI) subjects is that the stimulation should elicit a sufficiently powerful muscle contraction, while causing only minimal fatigue. Generally fibers innervating fast-twitch, fast-fatigue motor units (type IIb) are more readily recruited than fibers innervating slow-twitch, fatigue-resistant motor units (type I). Moreover after SCI, normal fiber type composition converts to a predominantly fast-twitch, fast-fatigue fiber type composition (e.g., IIa: 30%, IIb:70%), which contributes to the compromised performance of the muscle.

Recent findings on the variation of fatigue rate with frequency[1] in able-bodied persons have renewed interest in kHz frequency alternating current stimulation. It could be proven that because of the selective dropout of fast-twitch, fast-fatigue fibers at higher kHz frequencies, there is a greater proportional contribution of slow-twitch, fatigue-resistant motor units at those frequencies, i.e., the fatigue rate reduces monotonically in the 1-10 kHz range. While maximum electrically induced torque decreases with increasing frequency, the reduced fatigue rate at higher alternating current frequencies is bought at the price of reduced maximum evocable force. It is not known if a selective dropout of fast-fatigue muscle fibers IIb takes place in SCI subjects.

Therefore the question arose as to whether it is possible in the case of MFAC stimulation of the weak (torque = 7-10% of MVC typically) and rapidly fatiguing leg musculature of subjects with SCI to find a balance between fatigue rate and force at which a higher functional outcome of movement could be achieved than in the case of classic LFRP stimulation. Thus, MFAC and standard LFRP stimulation were compared in the light of the functional outcome-relevant parameters of a readily controllable FES modality of SCI subjects, FES cycling: the evoked maximal short time isometric torque, work generated in a fixed time interval (instead of fatigue rate), and also pain sensation.

2. METHODS

Eleven subjects with predominantly complete spastic SCI were recruited. The subjects with lesions at level C5-Th12, who had no previous FES-cycling training, underwent three experimental sessions at three different dates in an arbitrary sequence: 1. isometric measurements using LFRP and MFAC stimulation, 2. ergometry using LFRP stimulation, and 3. ergometry using MFAC stimulation. A low frequency constant current eight-channel stimulator provided the LFRP current (rectangular, bi-phasic equilibrated stimulation current with a frequency of 20 Hz, covering an intensity range of 0-127 mA and maintaining a pulse width of 500 µs). A middle frequency constant current (MFAC) six channel stimulator provided the 4 kHz sinusoidal current modulated with 50 Hz on-off rectangles with duty cycle 1:1. Stimulators were laptop controlled by serial communication ports, in both the isometric measurement and the ergometer cycling setup (Fig.1).

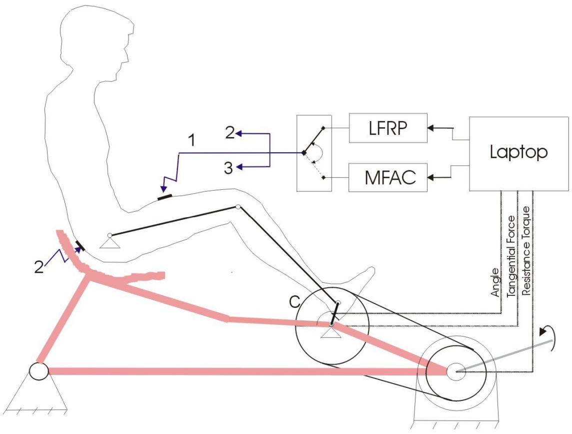

Fig.1. Experimental setup for isometric and dynamic measurements. Abb: 1=quad, 2=glu, 3=ham muscle.

During isometric measurements the individual torque profiles (crank torque vs. crank angle) of the six stimulated muscle groups (quadriceps, gluteus, hamstrings) were determined for all patients with a torque sensor mounted on a stationary tricycle (Fig.1). An eight-bit incremental encoder, synchronized to turn with the crank shaft, determined the actual position of the crank.

To determine 20-minutes of pedaling work FES-cycling was performed on a motor-braked ergometer (Fig.1) which allowed the resistive torque to be read by a laptop computer. Pedaling work was computed as the integral of cadence x crank torque over the 20 minutes of stimulation.
For statistical analysis of mean maximal isometric torque and 20-minutes of pedaling work, the nonparametric paired-sample Wilcoxon test and Spearman rank correlation were applied, and statistical tests were considered significant if $p < 0.05$.

3. RESULTS

Representative sample data collected during isometric measurements of subject No. 10 are given in Figs. 2A and B. Besides the clear advantage of LFRP mean isometric torque over MFAC mean isometric torque (14.9 vs. 13.6 Nm), slight shape differences of the torque profiles can be observed. This is due to the different tissue depths reached by LFRP and MFAC stimulation. Moreover, the analysis of the power course collected in ergometric measurements of subjects 10 and 9 (Figs. 3A and B, respectively) shows that the 20-minute pedaling work during LFRP is also superior to that during MFAC stimulation (13717 vs. 7007 and 8152 vs. 6001 J, respectively).

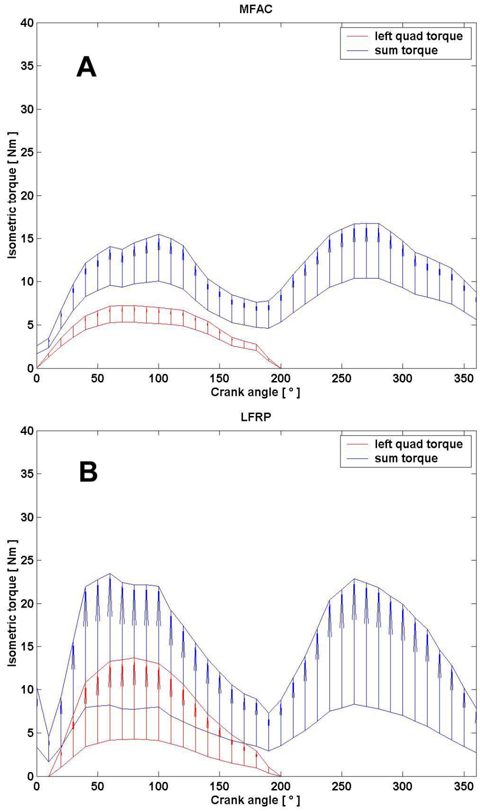

Fig. 2. Isometric torques of left quadriceps muscle (red) and the sum of all torques together (blue) produced when the subject No. 10 pedaled in positive drive direction with middle frequency alternating current (MFAC, A) and low frequency (LFRP, B) stimulation. (maximal torques: tip of arrowheads)

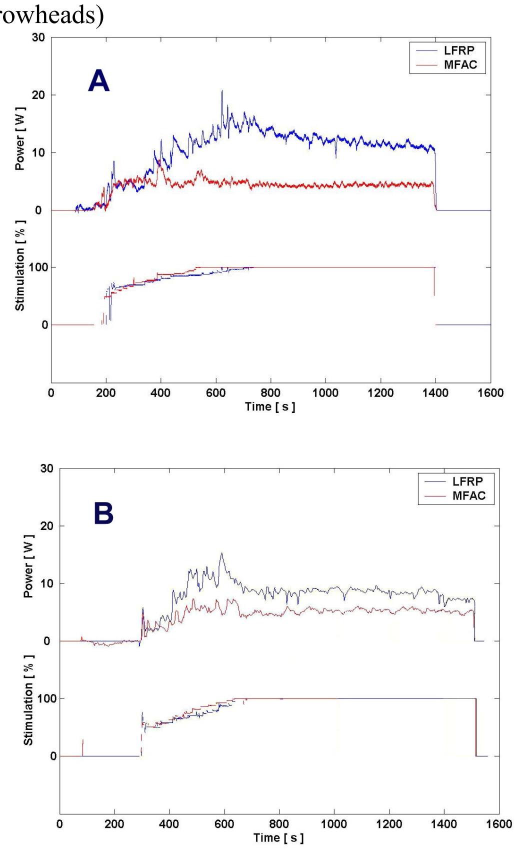

Fig. 3. Power course (upper graphs) of subjects No. 10 (A) and No. 9 (B) generated during 20 minutes of FES-ergometry using low frequency (LFRP, blue) and middle frequency alternating current (MFAC, red) stimulation. 20-minute pedaling work was defined as the area under the corresponding curves. Lower Graphs: Stimulation course expressed in % of maximal stimulation (LFRP blue, MFAC red).

An inspection of LFRP and MFAC stimulation conditions for all patients using descriptive statistics (Fig. 4) gave maximal isometric torques of 16.6 ± 10.6 Nm and 14.2 ± 10.0 Nm (n=10), respectively, and 20-minute work of 8445 ± 5552 J and 4716 ± 1834 J (n=11), respectively.

The non-parametric Wilcoxon paired-sample test proved that the isometric torque elicited during standard LFRP stimulation was significantly greater ($T_{-}=8$; $p< 0.02$) and also the 20-minute pedaling work generated during LFRP was highly and significantly greater ($T_{-}=0$; $p<0.001$) than during MFAC stimulation.

4. DISCUSSION AND CONCLUSIONS

The major findings of this study are that LFRP stimulation is superior to MFAC in producing isometric torque and dynamic cycling work by paralyzed skeletal leg muscles of SCI subjects. That LFRP isometric torque is superior to MFAC torque was expected and is similar to findings in able-bodied subjects.

The second important finding showed that the pedaling work produced during the first 20 minutes of cycling is higher during maximal stimulation with LFRP than with MFAC. A comparison of LFRP and MFAC conditions showed that 20-minutes of pedaling work diminished more (average 59% = 4716 J / 8445 J) than maximal isometric torque (average 86% = 14.2 Nm / 16.6 Nm). This means that the reduction of the maximally evocable torque during MFAC is accompanied by an increased fatigue rate in SCI patients, although a decreased fatigue rate was expected on the basis of the effect of MFAC stimulation on able-bodied subjects.

The MFAC stimulation in SCI people thus causes more dynamic fatigue (compared to isometric fatigue) than LFRP stimulation does. There are possibly two reasons for this: 1 High frequency fatigue (MFAC is energetically more demanding than LFRP stimulation)

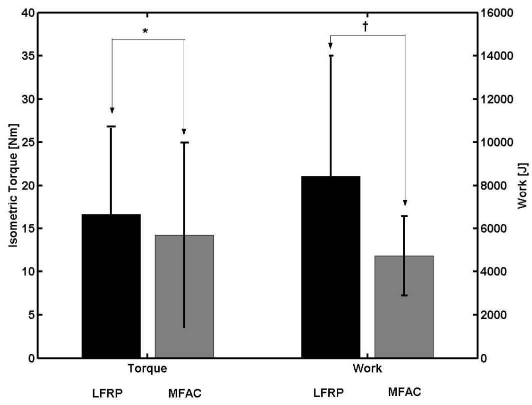

Fig. 4. Mean isometric torque of n = 10 study participants (left) and work generated during 20 minutes FES-ergometry (right) of all study participants (n = 11), using 20 Hz low frequency rectangular pulse (LFRP, black) and medium frequency alternating current (MFAC, gray) stimulation. * $p < 0.02$ and † $p < 0.001$.

and 2. The selective dropout of fast-fatigue IIb fibers in the case of MFAC stimulation actually signifies a change into a slow fatigue IIa type of muscle with a reduced power output.

Further work is necessary to decide whether a selective dropout mechanism that depends on the fatigue properties of fibers is actually responsible for differing fatigue rates during MFAC and LFRP stimulation of SCI muscle or if only a nonselective mechanism like higher energy demand in the case of MFAC has to be considered.

From a practical viewpoint, our results show that the force produced by fast-fatigue fibers in FES cycling of persons with SCI (or simply by more fibers if nonselective dropout) cannot be dispensed with in LFRP stimulation.

References

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Acknowledgements

This work was supported by the Else Kröner-Fresenius Foundation.