Does cycling training augmented by Functional Electrical Stimulation impact on muscle synergies in post-acute stroke patients?

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***Abstract*—Cycling induced by Functional electrical stimulation (FES) was proposed as a method to improve motor recovery after stroke. This study aimed at assessing the effects of this training on motor patterns of muscle co-activations, referred as muscle synergies. Seven post-acute patients underwent 15 sessions of FES-cycling training. Outcome measures were Motricity Index and gait speed collected before (T0) and after (T1) the intervention. Subjects were also involved in a cycling test during which four muscle synergies were extracted from 9 lower limb muscles and compared with a healthy control group. Results showed a significant improvement in terms of gait speed, which increased from a median value of 81.0cm/s at T0 to 100.0cm/s at T1. Trends of improvement in both spatial and temporal components of muscle synergies were also achieved. More data are needed to drive final conclusions about the effects of FES-cycling on muscle synergies but first results are promising.**

I. INTRODUCTION

STROKE is one of the most common neurological diseases, with a high social and economic impact. Post-stroke individuals often show poor muscular coordination [1]. Rehabilitative treatments are focused on the recovery of the walking ability. Cycling training augmented by Functional Electrical Stimulation (FES) has been recently shown to be effective to improve the recovery of locomotion [2], [3], integrating different key ingredients of motor (re)learning.

A promising approach to assess motor recovery is the study of muscular coordination through muscle synergies, analyzing their timing and spatial components [4], [5]. However, up to now muscle synergies have been studied mainly during walking [4], [5], while only one work evaluated the modular control during cycling in post-stroke patients [1]. The results of this study supported the study of muscle synergies during pedaling as an assessment method in the early phase after stroke, when patients can be still unable to walk independently.

The present study aimed at examining the effects of volitional cycling training augmented by FES on the spatial composition and timing of muscle synergies during cycling in a sample of post-acute stroke patients.

II. MATERIAL AND METHODS

A. Participants and study design

Seven males who experienced an ischemic stroke (<6 months) were enrolled in the study (median [interquartile range IQ] age of 74.0[12.0] years, 14.0[7.5] days post stroke).

Participants underwent a three-weeks training composed by 15 25-min sessions of FES-augmented voluntary pedaling (MOTOmed Viva2, Reck GmbH), followed by 60 min of usual care. FES was delivered to the quadriceps, hamstrings, tibialis anterior and gastrocnemius lateralis muscles of both legs (RehaMove2TM, Hasomed GmbH). During the training, a visual feedback of the force produced at the two pedals (Powerforce TM, Radlabor GmbH) was provided to the patients to help them perform a symmetrical task

Lower limb motor impairment was assessed before (T0) and after (T1) the intervention through i) the lower limb subscale of the Motricity Index (MI), whose score ranges from 0 (maximal impairment) to 100 (no impairment); ii) a 10-meter walking test to assess gait speed (V) (GaitRite, CIR systems Inc.); iii) a cycling test, consisting of 1 minute of passive pedaling (i.e. only supported by the cycle-ergometer motor) followed by 2 minutes of active pedaling at 30 revolutions per minute (RPM) with a customized resistance. During the cycling test, a signal amplifier (Porti 32, TMSI) was used to acquire EMG signals from 9 leg muscles bilaterally (Gluteus Maximus, Biceps Femoris long and short head, Gastrocnemius Medialis, Soleus, Tensor Fasciae Latae, Rectus Femoris, Vastus Lateralis, and Tibialis Anterior).

B. Data analysis and statistics

Thirty revolutions with a cadence of 30±4 RPM were selected for the analysis. The active force produced during pedaling was computed subtracting the mean profile obtained during the passive phase from the one obtained during the voluntary pedaling phase. The work produced by both the affected (L_A) and unaffected (L_U) leg were then computed as the integral of the active force profile and averaged among all

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revolutions. Finally, the pedaling unbalance was calculated as follows [1]:

$$U\% = \frac{|L_U - L_A|}{L_U + L_A}\% \quad (1)$$

EMG signals were pre-processed (3rd order Butterworth band-pass filter at 20-400 Hz, rectification and low-pass filter at 5 Hz) to compute the EMG envelope, resampled on a 360-points vector with a cubic spline approximation and normalized over the median peak value obtained among the 30 revolutions. Non-Negative Matrix Factorization (NNMF) was used to extract *N* muscle synergies in such a way that M≈WH, where *W* are the synergy vectors and *H* the synergy activation coefficients. The number *N* of modules was computed as the minimum number able to account for at least 90% of the Variance Accounted For (VAF) computed as follows:

$$VAF = 1 - \frac{\sum\sum(M - W*H)^2}{\sum\sum(M)^2} \quad (2)$$

Then, the NNMF algorithm was applied fixing the number of synergies to 4 in order to allow a comparison with previous results achieved on a group of age matched healthy subjects ($W_{heatlhy}$ and $H_{healthy}$) [1]. The similarity (SIM) was quantified by using the cosine of the angle between the synergy vectors *W* obtained by the affected side of the patients and $W_{healthy}$ [5]. The synergy activation coefficient *H* were finally compared with $H_{healthy}$ by means of the Shape Symmetry Index (SSI) [1] computed as follows:

$$SSI_j = \frac{C_{Hj\ \ Hj\,healt}}{\sqrt{\sum_{i=1}^{360} H_j^2(i) + \sum_{i=1}^{360} H_{j\,healthy}^2(i)}} \quad (3)$$

where H_j is the activation coefficient for the j-th synergy, $H_{j\,healthy}$ is the activation coefficient of the corresponding synergy vector of the healthy control group, $C_{Hj\ \ Hj\,healthy}$ is the circular cross-correlation function at lag 0. SSI ranges from -1 to 1 (i.e., identical profiles shape). Synergies were matched based on the scalar product between them.

The statistical analysis was performed in SPSS Statistics v23 software. Changes between T0 and T1 were evaluated with the non-parametrical Wilcoxon test for paired samples.

III. Results

Results are reported in Table I. A statistically significant improvement in terms of MI, gait speed and work produced by the affected leg during pedaling was obtained.

The number of muscle synergies ranged between 3 and 4 for all the patients both at T0 (N=4 for 4 patients) and T1 (N=4 for 1 patient). An increasing trend of both SIM and SSI was obtained, of higher magnitude for synergy 3 (co-activation of knee flexors) and 4 (co-activation of ankle dorsal-flexors and hip flexors) that intervene in the pulling phase of the pedaling cycle, as detailed in [1].

TABLE I

Median(IQ) values of the outcome measures.

		T0		T1		T0vsT1 p-value
MI_A		75	[8]	91	[17]	**0.02**
V [cm/s]		81.0	[41.1]	100.0	[24.0]	**<0.01**
L_A[Nm]		30.2	[13.6]	37.9	[24.7]	**0.01**
L_U [Nm]		34.3	[19.2]	40.9	[5.1]	0.22
U%		14.2	[9.0]	11.3	[4.0]	0.05
SIM	W1	0.83	[0.07]	0.92	[0.07]	0.09
	W2	0.82	[0.07]	0.81	[0.13]	1.00
	W3	0.50	[0.31]	0.92	[0.23]	0.08
	W4	0.89	[0.09]	0.98	[0.04]	0.05
SSI	H1	0.81	[0.21]	0.92	[0.13]	0.39
	H2	0.70	[0.24]	0.89	[0.16]	0.58
	H3	0.59	[0.46]	0.87	[0.40]	0.47
	H4	0.88	[0.27]	0.93	[0.11]	0.09

MI: motricity index, V: gait velocity, $L_{A/U}$: work affected/unaffected, U: unbalance, SIM: similarity, SSI: Shape Symmetry Index, W: synergy vectors; H: synergy activation coefficients; p-value: Wilcoxon test

IV. Discussion

The achieved results support improvements in terms of motor outcome and neuro-mechanics of the motor gesture. Specifically, the significant increase of MI, V and L_A suggest that the training was effective to improve muscle strength and locomotion ability, as expected from the results of previous studies [2], [3]. The analysis of muscle synergies at baseline showed wide differences between patients and healthy controls, mainly for synergy 3 (SIM=0.50 [0.31] and SSI=0.59 [0.46]), supporting a higher level of impairment for both spatial and temporal synergy components during the pulling phase of the cycle (foot moving towards pelvis). This result is in line with the decreased knee flexion which typically characterizes stroke patients. After training, an apparent trend of improvement both in terms of spatial and temporal component of synergy 3 was observed, suggesting the capability of FES cycling training to improve muscle coordination after stroke. However, this trend was not significant, probably due to the reduced sample size.

To conclude, this is the first study investigating the longitudinal effects of FES cycling on modular coordination. The results are promising but need to be confirmed on a wider sample size. A control group is also needed to compare the effects induced by FES cycling with respect to usual care.

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