Cycling Induced by Electrical Stimulation Improves Motor Recovery in Postacute Hemiparetic Patients

A Randomized Controlled Trial

Emilia Ambrosini, MS; Simona Ferrante, PhD; Alessandra Pedrocchi, PhD; Giancarlo Ferrigno, PhD; Franco Molteni, MD

Background and Purpose—This study assessed whether cycling induced by functional electrical stimulation (FES) was more effective than passive cycling with placebo stimulation in promoting motor recovery and walking ability in postacute hemiparetic patients.

Methods—In a double-blind, randomized, controlled trial, 35 patients were included and randomized to receive FES-induced cycling training or placebo FES cycling. The 4-week treatment consisted of 20 sessions lasting 25 minutes each. Primary outcome measures included the leg subscale of the Motricity Index and gait speed during a 50-meter walking test. Secondary outcomes were the Trunk Control Test, the Upright Motor Control Test, the mean work produced by the paretic leg, and the unbalance in mechanical work between paretic and nonparetic legs during voluntary pedaling. Participants were evaluated before training, after training, and at 3- to 5-month follow-up visits.

Results—No significant differences were found between groups at baseline. Repeated-measures ANOVA ($P<0.05$) revealed significant increases in Motricity Index, Trunk Control Test, Upright Motor Control Test, gait speed, and mean work of the paretic leg after training and at follow-up assessments for FES-treated patients. No outcome measures demonstrated significant improvements after training in the placebo group. Both groups showed no significant differences between assessments after training and at follow-up. A main effect favoring FES-treated patients was demonstrated by repeated-measures ANCOVA for Motricity Index ($P<0.001$), Trunk Control Test ($P=0.001$), Upright Motor Control Test ($P=0.005$), and pedaling unbalance ($P=0.038$).

Conclusions—The study demonstrated that 20 sessions of FES cycling training significantly improved lower extremity motor functions and accelerated the recovery of overground locomotion in postacute hemiparetic patients. Improvements were maintained at follow-up. **(*Stroke*. 2011;42:1068-1073.)**

Key Words: functional electrical stimulation ■ hemiparesis ■ motor relearning ■ randomized controlled trials ■ rehabilitation

Hemiparesis is a partial loss of motor function of one side of the body, mainly caused by hemorrhagic or ischemic strokes. Hemiparesis occurs in 88% of individuals who experienced a stroke,[1] and it ranks as the leading cause of severe and long-term disability. Traumatic brain injury is another cause of hemiparesis. Overall incidence, which includes causes other than stroke, is difficult to predict.

Neurological deficits typically improve in the first weeks after injury because of brain plasticity, which encompasses all possible mechanisms of neuronal reorganization, such as recruitment of pathways functionally homologous to, but anatomically distinct from, the damaged ones, synaptogenesis, dendritic arborization, and reinforcement of existing but functionally silent synaptic connections.[2] Recovery can vary greatly, even among patients with identical clinical severity in the acute phase. The understanding of the mechanisms that promote or prevent recovery is crucial to the design of optimized therapies. During this process, motor activity and sensory feedback are fundamental.[2] Several studies have associated elements of afferent stimulation with beneficial changes in brain activity, including repetition,[3] functional goal-directed activity,[4] and functional electrical stimulation (FES).[5–7] Clinical evidence suggests that FES-mediated therapy reduces motor impairment for persons with hemiparesis.[8]

Restoration of walking is considered the main goal of poststroke lower limb rehabilitation, with gait speed regarded as a reliable marker of deficit severity.[9] Since the 1990s, FES has been increasingly used in poststroke gait rehabilitation, given some evidence of its effectiveness in improving motor and walking ability.[10,11] A safe and economic alternative to

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FES-induced gait training is the use of FES synchronized to the cycling movement, which entails a coordinated activation of the lower limb muscles, approximating the cyclic movements of locomotion. The feasibility of FES-induced cycling training on postacute[12,13] and chronic[14,15] stroke patients has been recently shown. These studies suggest that FES cycling is effective in improving muscle strength,[12] cycling smoothness,[13] and peak pedaling power.[15] A key question is whether FES-mediated training on a motorized cycle ergometer translates to improvements in overground locomotion. Alon et al[15] tried to answer this question, but only a limited number of chronic stroke patients (n=10), already able to walk, was recruited in their feasibility study; moreover, they did not include a control group to strengthen their results. Because of the similarities between cycling and walking and the afferent–efferent stimulation provided by FES, we hypothesized that FES-induced cycling applied in the postacute phase could play a crucial role in promoting motor recovery and improving locomotion. The aim of our study was to investigate whether FES-induced cycling was a more effective intervention for postacute hemiparetic patients than passive cycling with placebo stimulation.

Patients and Methods

Participants

Thirty-five patients, inpatients of Villa Beretta, were recruited from May 2008 to July 2009. Participants satisfied the following inclusion criteria: diagnosis of a first-time stroke (n=32) or traumatic brain injury (n=3), resulting in hemiparesis; acute event interval <6 months before study onset; sufficient cognition (evaluated by the physician with a normal procedure) to perform active standard rehabilitation; able to sit up to 30 minutes; joint mobility ranges that would not preclude pedaling; and low spasticity in the lower limb muscles (modified Ashworth score <2). Exclusion criteria were cardiac pacemakers, allergy to electrodes, and an inability to tolerate stimulation. All patients received an information sheet and provided their written informed consent. The research protocol was approved by the medical ethics committee of the Valduce Hospital.

Design

A double-blind, randomized, clinical trial was conducted. Patients were randomly allocated into 2 groups receiving cycling training synchronized to FES (FES group) or passive cycling training with FES placebo (placebo group). A computer-generated randomization sequence was made and an automated assignment system was used to ensure allocation concealment. Both patients and assessors were unaware of group assignment. Subjects were tested before the intervention, after the intervention, and during a follow-up assessment 3 to 5 months after the end of the treatment.

Intervention

Both intervention groups were trained 5 times per week, receiving a total of 20 sessions lasting 25 minutes each. In addition to the assigned group treatment, subjects performed their own standard rehabilitation program, which consisted of 3 hours per day of physical therapy, including stretching, muscular conditioning, exercises for trunk control, standing, and walking training. During treatment, participants were seated on a chair in front of a motorized cycle-ergometer (MOTOmed; Reck GmbH). A current-controlled 8-channel stimulator (RehaStim; Hasomed GmbH) was used and surface electrodes were applied in a bipolar configuration on quadriceps, hamstrings, gluteus maximum, and tibialis anterior of both legs. Rectangular biphasic pulses with pulse width of 300 μs and stimulation frequency of 20 Hz were adopted. For FES-treated subjects, the stimulus intensity was set on each muscle at a tolerated value producing visibly good muscle contractions, whereas subjects in the placebo group received stimuli of zero intensity. To promote a similar mental set, participants were informed before treatment that they might or might not feel the stimulation. The stimulation timing was synchronized to the cycling movement according to physiological stereotype activation patterns.[12] All sessions consisted of a 5-minute warm-up of passive cycling, a 15-minute training of FES cycling or placebo FES cycling (ie, passive cycling with electrodes attached correctly on the skin without delivering any stimulation current), and a 5-minute cool-down of passive cycling. Patients were required not to contribute voluntarily to the pedaling but to keep concentrating on the exercise. During passive cycling, the subject's legs were moved solely by the ergometer's motor, which guaranteed a constant speed of 20 rpm throughout the training session. Figure 1 shows the experimental set-up.

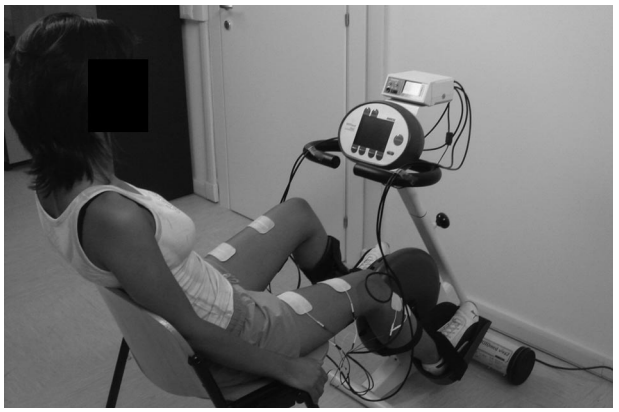

Figure 1. Experimental set-up used for the intervention.

Outcome Measurements

The International Classification of Functioning, Disability and Health classifies health domains by means of a list of body functions and structure, and a list of domains of activity and participation.[16] According to this classification, the leg subscale of the Motricity Index (MI), which evaluates motor power of the paretic lower extremity and ranges from 0 to 100,[17] was chosen as a primary outcome measure related to body functions. The overground walking speed was identified as a primary outcome measure within the activity domain. The gait speed was measured by timing a walk of 50 meters with a stopwatch and was regarded as zero if the test was not completed. Subjects were asked to walk at a self-selected speed, using walking aids if necessary. This test was chosen because a 50-meter distance is representative of the typical indoor walking need of patients.[12] Secondary outcome measures included the Trunk Control Test (TCT), which, scored from 0 to 100, evaluates trunk control,[18] and the Upright Motor Control Test (UMCT), which, scored from 0 to 6, assesses functional abilities of the impaired leg during single-limb standing.[19] Moreover, patients' ability to perform an active, coordinated, bilateral movement, strongly related to both treatments, was assessed through a pedaling test. During this test, participants were seated on a chair in front of a motorized cycle ergometer (Thera-Live; Medica Medizintechnick GmbH) customized with resistance strain gauges mounted on the crank arms to measure the torque generated by each leg during pedaling.[20] Each trial consisted of 1 minute of passive cycling, followed by 2 minutes of voluntary pedaling, during which time subjects were asked to pedal, concentrating on the task symmetry. Throughout the trial, the ergometer's motor maintained a minimum speed of 30 rpm to guarantee a smooth and safe movement. A personal computer using Matlab/Simulink under Linux was used to acquire the crank angle and the torque signals, with a sampling frequency of 200 Hz. For each revolution of voluntary pedaling, the work produced by each side was computed as the integral of the active torque profiles mapped as function of the crank angle. The active torques were estimated by subtracting the passive torques from the measured total

torques.[21] The mean work produced by the paretic and healthy legs, W_{PL} and W_{HL}, respectively, were calculated by averaging all single-revolution values. The pedaling unbalance, U, was obtained as follows:

$$U=\frac{|W_{HL}-W_{PL}|}{|W_{HL}|+|W_{PL}|}$$

U could range from 0% (identical work produced by both legs) to 100% (W_{PL} negative or equal to 0).

Statistical Analysis

Statistical analysis was performed using STATISTICA version 8.0. The baseline characteristics were compared in the 2 groups by *t* test for age, time since brain injury onset, gait speed, and Mann-Whitney *U* test for MI. For patients who missed the follow-up assessment, scores after training were used to replace missing data. The effects of time were determined by using repeated-measures ANOVA whereas the effect of group was determined by using repeated-measures ANCOVA with baseline as the covariate ($P<0.05$).[22] If the repeated-measures ANCOVA revealed a significant effect based on pooled scores (after training and follow-up), then post hoc analysis using ANCOVA dealing separately with assessments after training and at follow-up was performed and mean differences (95% CI) between groups were computed. Effect sizes were calculated using partial eta-squared (η^{2p}). Sample size was defined on the basis of ability to detect a minimal clinically important difference for gait speed, estimated as 0.16 m/s with a standard deviation of 0.22 m/s.[9,23] A sample of 30 subjects allows achievement of 80% power and significance level of 0.05. To allow a 15% drop-out rate, 35 patients were recruited.

Results

Thirty-five patients were recruited in the study and 30 who completed 20 sessions of training were included in the analysis. Fifteen received FES cycling training and 15 received placebo FES cycling training (Figure 2). Table 1 outlines the characteristics and the scores before training of the participants. There were no significant differences between groups in terms of demographics variables and primary outcome measures at baseline. Participants allocated to the placebo group showed a better score on TCT, although no significant difference was found. Eight patients (4 in the FES group and 4 in the placebo group) discontinued the study before follow-up assessments. Follow-up evaluations took place 112±25 and 105±25 days after treatment for the FES and placebo group, respectively.

FES-treated patients demonstrated significant improvements in both primary outcome measures after intervention (Table 2). The MI score increased from 39 to 69 ($P<0.001$) and gait speed increased from 0.11 m/s to 0.39 m/s ($P=0.028$). Improvements were maintained at follow-up. Significant main effects also were found across time in terms of TCT, UMCT, and W_{PL}. The placebo group showed no significant changes in all primary and secondary outcome measures after treatment, whereas statistically significant improvements occurred at follow-up in both primary outcomes (MI, $P=0.002$; gait speed, $P=0.001$). No outcome measures showed significant differences between assessments after training and at follow-up for both groups.

Repeated-measures ANCOVA with baseline as covariate showed a significant time-by-group interaction in MI, TCT, UMCT, and pedaling unbalance in favor of the FES group. Post hoc analysis revealed a main effect of group in favor of FES-treated patients for all these measures immediately after training and for MI, TCT, and UMCT at follow-up (Table 3). Differences between groups in terms of gait speed and W_{PL} were not statistically reliable; however, both outcomes were better for patients receiving FES cycling training (mean differences based on pooled scores [95% CI]: gait speed, 0.19 m/s [−0.23 to 0.60]; W_{PL}, 11.03 Nm [−2.43 to 24.49]).

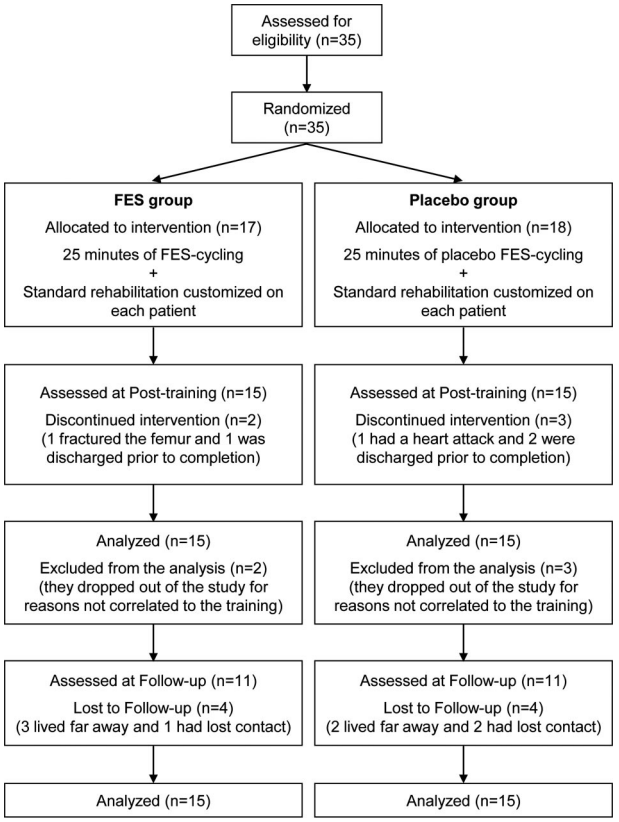

Figure 2. Participant CONSORT flow chart.

Discussion

According to International Classification of Functioning, Disability and Health human functioning can be classified

Table 1. Participant Baseline Characteristics

	Placebo	Functional Electrical Stimulation	*P*
Age, years*	56 (14)	59 (10)	0.499‡
Time since brain injury onset, days*	48 (36)	48 (43)	0.992‡
Gender (male/female)	7/8	11/4	
Etiology (ischemic/hemorrhagic/ traumatic brain injury)	8/5/2	11/3/1	
Hemiparesis side (right/left)	7/8	6/9	
50-meter walking test (able/ not able)	4/11	3/12	
Motricity index†	40 (57)	38 (55)	0.708§
Gait speed (m/s)*	0.11 (0.24)	0.11 (0.25)	0.995‡

*Mean (SD).
†Median (interquartile range).
‡*t* test for independent samples.
§Mann-Whitney *U* test.

Table 2. Comparisons of Outcome Measures Before Training, After Training, and During Follow-Up

	Group	Before Training*	After Training*	Follow-Up*	P† (Before vs After)	P† (Before vs Follow-Up)	P† (After vs Follow-Up)	P‡ (η^2_p)
Primary measures								
Motricity index	Placebo	45 (34)	55 (29)	63 (25)	0.230	0.002	0.552	<0.001 (0.367)
	FES	39 (26)	69 (29)	79 (24)	<0.001	<0.001	0.243	
Gait speed (m/s)	Placebo	0.11 (0.24)	0.29 (0.28)	0.48 (0.46)	0.357	0.001	0.314	0.366 (0.030)
	FES	0.11 (0.25)	0.39 (0.30)	0.57 (0.34)	0.028	<0.001	0.314	
Secondary measures								
TCT	Placebo	58 (20)	67 (17)	69 (17)	0.511	0.215	0.995	0.001 (0.331)
	FES	46 (19)	78 (25)	85 (22)	<0.001	<0.001	0.719	
UMCT	Placebo	1.7 (1.9)	2.3 (1.9)	2.9 (1.7)	0.691	0.095	0.853	0.005 (0.258)
	FES	1.4 (1.5)	3.7 (1.7)	4.1 (2.1)	<0.001	<0.001	0.911	
W_{HL} (Nm)	Placebo	20.64 (16.63)	24.91 (13.14)	25.47 (10.63)	0.882	0.815	1.000	0.144 (0.080)
	FES	23.06 (14.48)	29.99 (14.79)	32.54 (10.52)	0.438	0.122	0.984	
W_{PL} (Nm)	Placebo	3.68 (7.45)	5.79 (8.87)	5.79 (8.38)	0.947	0.947	1.000	0.104 (0.098)
	FES	6.46 (7.84)	13.28 (13.24)	14.25 (12.35)	0.036	0.010	0.998	
Unbalance (%)	Placebo	75 (36)	75 (32)	71 (30)	1.000	0.992	0.993	0.038 (0.155)
	FES	67 (33)	53 (35)	52 (33)	0.130	0.087	1.000	

FES indicates functional electrical stimulation; TCT, Trunk Control Test; UMCT, Upright Motor Control Test; W_{HL} and W_{PL}, the works produced by the healthy and paretic legs, respectively.

*Mean (SD).

†*P*=significance level of repeated-measures ANOVA (post hoc Scheffè).

‡*P*=significance level of repeated-measures ANCOVA with baseline as covariate.

into 3 levels: functioning at the level of body, the whole person, and the whole person in a social context. Therefore, disability involves dysfunctioning at one or more of the following levels: impairments (problems in body function), activity limitations (difficulties in executing activities), and participation restrictions (problems in involvement in life situations).[16] The results of this study demonstrated that 20 sessions of FES-induced cycling training significantly reduced both impairments and activity limitations in postacute hemiparetic patients. Functioning at the level of body was evaluated in terms of MI, TCT, and UMCT. In all these scores, significant differences between groups were found after training in favor of FES-treated subjects and were maintained at follow-up. These results showed a significant improvement of the whole kinetic chain, involving both leg and trunk, as demonstrated by MI and TCT and confirmed by UMCT. Trunk control is known to be an important prerequisite for the control of more complex limb activities;[24] therefore, identifying a treatment available in the early rehabilitation stage and able to enhance trunk control is essential to the subsequent recovery of functional tasks. In this context, FES cycling training seems to be a good candidate. Improvements in executing activities were tested during pedaling and walking. A significant difference between groups was found in terms of pedaling unbalance, demonstrating that FES cycling treatment may help in "re-

Table 3. Changes Between Groups After Training and at Follow-Up

	Assessment	Placebo*	FES*	Mean Difference (95% CI)	P† (η^2_p)
Primary measure					
Motricity index	Post-training	11 (4)	30 (4)	19 (8–30)	0.002 (0.306)
	Follow-up	10 (4)	39 (4)	21 (10–31)	<0.001 (0.357)
Secondary measures					
TCT	Post-training	12 (4)	32 (4)	20 (8–33)	0.003 (0.288)
	Follow-up	14 (4)	36 (4)	22 (10–35)	0.001 (0.321)
UMCT	Post-training	0.7 (0.3)	2.3 (0.3)	1.6 (0.7–2.5)	0.001 (0.321)
	Follow-up	1.3 (0.4)	2.7 (0.4)	1.4 (0.1–2.7)	0.032 (0.160)
Unbalance (%)	Post-training	0 (5)	−16 (5)	−16 (−31 to −1)	0.032 (0.164)
	Follow-up	−3 (6)	−17 (6)	−14 (−30 to 1)	0.074 (0.118)

FES indicates functional electrical stimulation; TCT, Trunk Control Test; UMCT, Upright Motor Control Test.

*Adjusted mean (SE).

†*P*=significance level of ANCOVA with baseline as covariate.

minding" subjects how to perform a symmetrical pedaling, whereas passive cycling alone does not show the same effectiveness. Concerning walking ability, the participants exhibited a general improvement after intervention. At baseline, only 20% of subjects in the FES group and 27% in the placebo group were able to walk 50 meters, whereas after training these percentages increased for both groups (87% and 80% for the FES and placebo group, respectively); this gain was further improved at follow-up. A significant increase in gait speed was evident after training and onward for participants receiving FES cycling, whereas the placebo group obtained significant improvements only at follow-up, giving some evidence that FES cycling promotes a faster recovery in terms of locomotion. However, no significant differences in walking speed between groups were remarked. Given that TCT score showed a significant difference in favor of the FES group and that TCT is a predictor of walking recovery,[24] we suppose that longer treatment could have highlighted a clearer difference between groups concerning gait speed. A subgroups analysis performed on ischemic stroke patients (n=11, FES group; n=8, placebo group) demonstrated a reliably higher gait speed after treatment for FES-treated patients when compared with subjects in the placebo group (P=0.014; mean differences based on pooled scores [95% CI], 0.54 m/s [0.12–0.96]).

A strength of the study was the participants' blindness to treatment group, ensuring that all patients received the same extent of attention by the therapists. Although complete blinding was potentially challenging because of the visible muscle contractions produced by "active" stimulation, no subjects seemed to be aware of the allocation group; also, no one asked for more explanations.

A possible limitation of the study was the heterogeneous population of participants. Although the optimal solution would be the definition of rehabilitative methods specific for each brain lesion etiology and location, neurological patients with different pathologies but affected by similar motor impairments often undergo similar treatments. Therefore, aiming at the functional assessment of FES cycling as a rehabilitative training rather than at the investigation of the neurological mechanisms that justify the efficacy of FES, we focused our study on neurological patients with homogenous functional disabilities. Hemiparesis was the common motor impairment, making all patients similar from a functional rehabilitative point of view. Another potential weakness of the study was the number of participants, which was quite limited even though it reached the sample size estimated in power calculations. A larger sample size could have strengthened a subgroups analysis, highlighting further results, as suggested by the analysis performed with ischemic stroke patients.

Still, the results confirmed our hypothesis that FES cycling training applied in the postacute phase could play a crucial role in facilitating and accelerating motor recovery in hemiparetic patients. These improvements could be explained by the increased sensorial input provided to the brain by FES. This effect is supported by a recent functional MRI study that demonstrated that FES-induced movements activated a significantly greater area in the sensorimotor regions than passive movements.[25] Moreover, FES cycling evokes afferences during the physiological activation phases of each muscle because of the adopted stimulation strategy,[12] which may help in relearning how to execute movements voluntarily. Finally, FES could have increased patients' commitment to the exercise compared to passive cycling.

Conclusions

A carryover effect from FES cycling training to overground locomotion has been demonstrated. The present study strongly supports that a 4-week treatment of FES-induced cycling improves motor recovery and walking ability in postacute hemiparetic patients. Improvements are maintained for at least 3 to 5 months after the end of the treatment.

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Disclosure

None.

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