Cycling induced by functional electrical stimulation improves the muscular strength and the motor control of individuals with post-acute stroke

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Aim. **The aim of this study was to investigate the effectiveness of cycling induced by functional electrical stimulation (FES) in patients with postacute stroke.**

Methods. **Twenty postacute inpatients were recruited and were randomly shared in a control group (56±9.2 years old, 50.8±24.5 days post-stroke) performing the standard rehabilitation (SR) and a FES group (51±12 years old, 56.1±22.8 days post-stroke) performing FES cycling in addition to SR. Both the groups performed 3 hours of rehabilitation per day for 4 weeks. The FES cycling was applied daily for 35 minutes and quadriceps, hamstring, gluteus maximus and tibialis anterior of both the legs were stimulated. The two groups were compared by the following outcome measurements before and after treatment: maximum isometric voluntary contraction (MVC) of quadriceps, walking and sit-to-stand ability, motricity index, upright motor control test and trunk control test.**

Results. **After the treatment, the U-Mann-Whitney test demonstrated that the FES group produced a significantly higher increase of the muscular force produced by both the quadriceps during MVC with respect to the control group (P<0.05). Seventy percent of FES patients learned how to perform the sit to stand movement with three different rising speeds while no control patients develop the ability to perform the task properly.**

Conclusion. **Rehabilitation including FES cycling was more effective in promoting muscle strength and motor recovery of the lower extremity than therapist-assisted SR alone. Tests on an enlarged number of patients are necessary for generalization before proposing FES cycling in the clinical rehabilitation of post-acute stroke patients.**

KEY WORDS: Electric stimulation therapy - Stroke - Rehabilitation - Muscle strength.

Stroke continues to be a major public health concern, with more than 750 000 new strokes occurring each year in the US. In Italy about 180 000 strokes per year occur among which the 80% are first strokes and the 20% are recurrent ones.[1, 2] Though the ictus incidence is decreasing in the last years, it remains the third leading cause of death behind heart disease and cancer and the leading neurologic cause of long-term disability.[1] The most common effect of a stroke is the hemiparesis that is a paralysis of one vertical half of the body. Hemiparesis is not a static phenomena: it foresees some degrees of motor recovery which depend, considerably, on the initial severity of the stroke and on the choice of rehabilitation.

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Several studies have revealed that motor experience plays a major role in the subsequent physiological reorganization occurring in the adjacent intact tissues.[3, 4] Clinical studies on central motor neuroplasticity support the role of goal-oriented, active, repetitive movement in the training of the paretic limb to enhance motor relearning and recovery in patients with stroke.[5] If goal-oriented, repetitive movement therapy facilitates motor relearning, it is possible that electrical stimulation-induced, goal-oriented, repetitive movement therapy furthermore facilitates motor relearning.[6, 7]

The application of functional electrical stimulation (FES) can reduce the time needed to the recovery of the individuals with stroke with respect to the standard rehabilitation.[8-10] Although the use of FES on upper extremities is well established in the rehabilitation of patients with hemiplegia, the possibility of applying FES to the lower limbs was tested recently by Yan *et al.*, showing interesting results.[9] FES was delivered to 4 muscles (quadriceps, hamstring, tibialis anterior and medial gastrocnemius) of the affected lower limb in order to recreate the walking sequence with the patient side-lying on the bed. This movement is very important but it was not produced bilaterally in the real walking environment. It can be hypothesized that cycling induced by FES could be more rehabilitative than this reproduction of walking because the patient can learn the proper motor strategy, as in the other study, but he can also have a sensorial bio-feedback on the symmetry of the movement and on the bilateral use of the legs.

The use of FES cycling on individuals with stroke seemed to be better than performing the passive movement alone because it provides the complete afference of the task to the patient, enhancing the synaptic controls needed to produce a well organized movement. This process can be crucial in a postacute phase of the hemiparesis because the patient could relearn the proper way to produce a movement. In addition, FES cycling can be performed in a very safe and comfortable position for patients. All these characteristics make this movement usable in the rehabilitation of the most of the stroke patients, also in a post-acute stage. In addition, the kinematic patterns of cycling are very similar to the ones of walking that is one of the most important motor function to recover in a stroke patient.[11, 12, 13] Both these tasks are cyclical, require reciprocal flexion and extension movements and have alternating muscle activations of antagonists in a well-timed and coordinated manner.

The aim of this study was to evaluate the clinical efficacy of FES cycling as a rehabilitation treatment supplementary to the standard rehabilitation (SR) for subacute stroke patients.

Materials and methods

Subjects and selection criteria

After given their informed consent, 20 patients with stroke were included in the clinical study.

The patients were postacute hemiplegics who were affected by an ischemic or hemorrhagic ictus. All of them were collaborative, able to understand simple instructions and able to sit in a wheelchair for about 45 minutes; in addition, a low spasticity for all the muscles of the lower limbs (Ashworth <2) and a good joint mobility (a knee extension up to 150° and a hip flexion up to 80°) were required. Patients with cardiac pacemaker or allergic to adhesives or electrodes were excluded.

Participants were randomly allocated to two groups: a control group performing the SR and a FES cycling group, performing FES cycling in addition to the SR. Patients were allocated into one of the two groups following a PC procedure. PC generated a random vector of N elements; the elements could be equal to 0 or 1 and the sum of all the elements was the half of the vector length. Each patient was randomly assigned to one position of the vector. Thus, if the element of the patient position was 0, the patient was treated with FES cycling, if it was 1 the patient was assigned to the control group. The vector position was cancelled after its extraction.

The SR performed with therapists included stretching, muscular conditioning with active or passive mobility, exercises to recover the trunk control, the standing position and walking training. Both the groups underwent about 3 hours a day of rehabilitation. The sequence and composition of exercises was customised on each patient. Patients demographic and clinical details are reported in Table I. The two groups were comparable in terms of age (56±9.2 years old for the control group and 51±12 for the FES group) and time elapsed from the ictus (50.8±24.5 days for the control group and 56.1±22.8 for the FES group).

TABLE I.—*Demographic and clinical details of the patients selected.*

Sub	Group	Sex	Age	Hemorragic/ Ischemic (HI)	Plegic side (L/R)	Days post ictus
1	C	M	58	I	L	50
2	C	M	66	H	L	26
3	C	F	58	I	R	32
4	C	F	50	I	R	68
5	C	F	46	I	R	70
6	C	M	64	I	L	18
7	C	M	67	I	L	42
8	C	M	58	I	L	37
9	C	F	59	I	L	68
10	C	F	38	H	R	97
11	F	F	60	H	R	45
12	F	F	33	H	R	54
13	F	F	34	I	L	96
14	F	M	40	I	L	51
15	F	F	60	I	R	64
16	F	M	57	I	R	46
17	F	M	59	I	R	22
18	F	F	70	I	R	76
19	F	M	50	I	R	78
20	F	M	49	H	L	29
Mean	C		56			50.8
Std	C		9.2			24.5
Mean	F		51			56.1
Std	F		12			22.8
#pnt	C	5M; 5F		2 H; 8 I		
#pnt	F	5M; 5F		3 H; 7 I		

For each subject the group, *i.e.*, FES cycling (F) or control group (C), sex, age, the ictus origin that could be hemorrhagic or ischemic (H/I), the affected side (L/R) and the number of days between the ictus and the beginning of the treatment (days post ictus) are reported.

Pre- and post-treatment tests

To compare the improvements produced by the rehabilitation on the two groups, the following clinical tests were selected and performed at the beginning and the end of the 20 days of treatment:

1. Trunk Control Test (TCT) evaluates trunk movements and balance while seated;[14]
2. Motricity Index (MI) is a general clinical test to evaluate the mobility of the ankle, knee and hip joint during voluntary movements performed against gravity or against an external resistance;[15]
3. Upright Motor Control Test (UMC) assesses functional muscle strength of the hemiplegic limb both in flexion and extension;[16]
4. walking test of 50 m represents the indoor walking ability of the patients;[17]
5. sit to stand trials to test motor control. Patients were asked to perform the movement at three different speeds: self-selected from the patient, one slower and one faster. The knee angle was measured by an electrogoniometer mounted on the knee of the affected limb. This test evaluates the motor control of the patient and in particular the ability to modulate the speed of execution;[17]
6. maximal voluntary contraction (MVC) measures the quadriceps isometric maximum force.[17] During this test the patient sat on a bench with the leg flexed and the knee angle fixed at 90°. The force was measured by load cell (L 2350/200LBS, Tekkal, Italy) mounted between the wall and the ankle. This test was carried out on both the legs.

Once preliminary tests had been conducted, the two different treatments started for the two groups.

FES cycling treatment

The FES cycling treatment was performed everyday for 4 weeks. Each trial lasts 35 minutes:

1. 5 minutes of passive cycling;
2. 10 minutes of FES;
3. 5 minutes of passive cycling;
4. 10 minutes of FES;
5. 5 minutes of passive cycling;

During all the sessions 4 muscular groups per each limb were stimulated: quadriceps, hamstrings, gluteus maximums and tibialis anterior. Every muscle was stimulated in a particular range of the crank angle, according to the Nitlab stimulation strategy.[18] This strategy, developed for individuals with spinal cord injury was modified substituting the stimulation of the gastrocnemius medialis with the tibialis anterior in order to achieve a better rehabilitation against the problem of drop foot. The crank angle was measured by a shaft encoder and it was acquired by a PC running Matlab/Simulink®.

The Thera–Live™ ergometer (Medica Medizintechnik GmbH, Germany) was chosen for the treatment. A current–controlled 8–channel stimulator, RehaStim Pro™ (Hasomed GmbH, Germany) was used. During the treatment, the patients sat on a chair in front of the ergometer and their legs were stabilized by two foot orthoses fixed to the pedals, so that the trial was safe and comfortable. It was possible to control the ergometer through a serial link, by changing the resistance and the speed or by directly setting the motor voltage with pulsewidth modulation. Passive

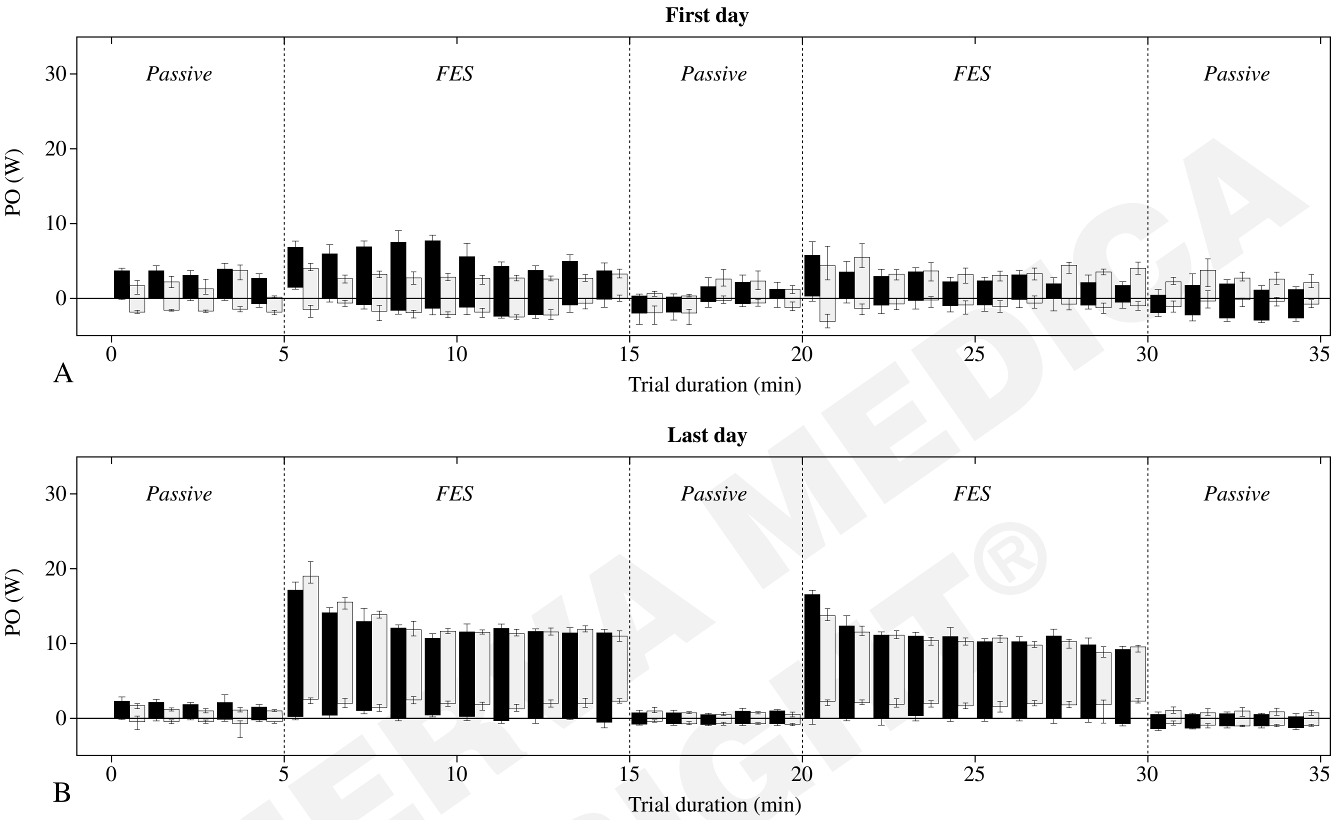

Figure 1.—Comparison between the first (A) and last (B) day of treatment in terms of median and quartiles of the minimum and maximum PO. For each minute of trial, white bars represent the PO produced in the half revolution in which the healthy leg was pushing. The black bars indicate the active PO obtained when the paretic leg was pushing.

cycling was guaranteed by a motor mounted in the ergometer and the speed was maintained at a constant value of 40 rpm during all the trials. Patients were explicitly required to not participate voluntary to the movement to assure a repeatable, symmetrical and smooth cycling.

Statistical analysis

To monitor the execution of the FES cycling treatment the power output (PO), *i.e.* the product between the torque and the speed, was considered. PO was calculated over each semi-revolution, to evaluate separately when the healthy leg and the paretic one were pushing. Active PO per semi-revolution was derived as the difference between the semi-revolution PO during FES phases and the average semi-revolution PO over the whole passive phases. Starting from the active PO, we computed the minimum and maximum value obtained in each half revolution per each minute of cycling.

The rehabilitation of the two groups was compared through the analysis of the clinical parameters (MI, TCT, UMC) and of all the other tests. In the walking test the speed of execution and number of steps were compared.

As for the sit to stand trial, the mean rising speed was computed in the slow, self-selected and fast trials. Then, the percentage ratio between the slow and self-selected speed and the percentage ratio between the fast and the self-selected speed were calculated. It was assumed that the patient was able to perform the motor task properly if the slow speed was less than the 90% of the fast one and if the fast speed was greater than the 110% of the self-selected one.

Finally, to compare the MVC trials the difference between the force produced in the post-treatment

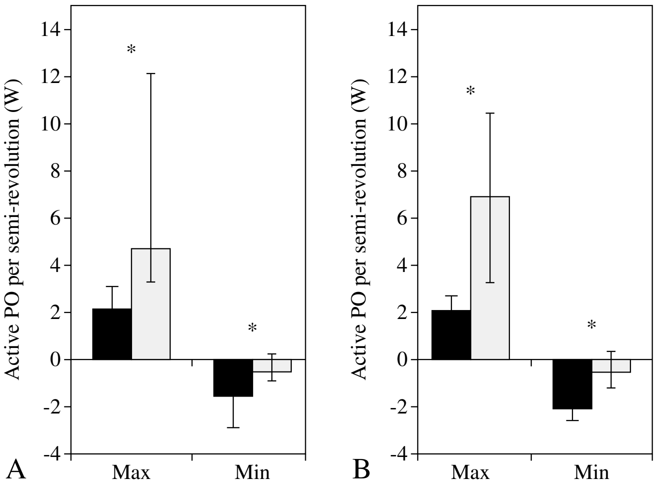

Figure 2.—Inter-subjective results obtained during the FES cycling treatment. The median and quartiles of the minimum and maximum active PO obtained in each semi-revolution are reported. The asterisks indicate when the results obtained in the first (black bars) and last (white bars) day are significantly different.

TABLE II.—*Results of the pre- and post-treatment clinical tests on control and FES patients.*

Sub	Group	TCT		MI		UMC flex		UMC ext	
		Pre	Post	Pre	Post	Pre	Post	Pre	Post
1	C	49	49	24	29	0	0	0	1
2	C	49	61	15	64	0	3	0	2
3	C	49	87	33	65	1	1	1	2
4	C	49	87	10	53	0	0	0	0
5	C	100	100	70	76	2	3	1	2
6	C	24	74	0	38	0	1	0	1
7	C	24	74	0	38	0	1	0	1
8	C	49	87	15	29	0	1	0	1
9	C	49	61	58	58	2	2	1	2
10	C	1	74	0	43	0	1	0	1
11	F	12	49	29	39	0	1	0	1
12	F	12	100	0	76	0	3	0	3
13	F	61	100	38	45	1	2	1	1
14	F	61	61	29	48	2	2	2	2
15	F	24	61	38	64	0	2	0	2
16	F	61	61	19	38	0	1	0	1
17	F	37	100	29	48	0	1	0	1
18	F	49	74	48	59	0	0	0	0
19	F	49	53	29	61	0	2	0	1
20	F	36	100	15	50	0	1	0	1
Median	C	49.0	74.0	15.0	48.0	0.0	1.0	0.0	1.0
25th	C	30.3	64.3	2.5	38.0	0.0	1.0	0.0	1.0
75th	C	49.0	87.0	30.8	62.5	0.8	1.8	0.8	2.0
Median	F	43.0	67.5	29.0	49.0	0.0	1.5	0.0	1.0
25th	F	27.0	61.0	21.5	45.8	0.0	1.0	0.0	1.0
75th	F	58.0	100	35.8	60.5	0.0	2.0	0.0	1.8

Clinical outcome measures such as MI, UMC, TCT, are reported per each patient before and after the treatment.

MVC test and the force produced in the pre-treatment MVC test (Δ MVC) was also computed.

After verifying with the Kolmogorov-Smirnov test that the variables were not normally distributed, a non parametric statistical analysis was carried out. In particular, the U-Mann-Whitney test, called also Wilcoxon Rank-Sum test, (P=0.05) was performed to compare the first and last day of the FES cycling treatment in terms of active PO produced in each semi-revolution.

Statistical analysis was then used to compare control and FES groups. Analysis was applied separately to the pre- and post-treatment tests. U-Mann Whitney test was carried out on all the discrete clinical indexes, *i.e.* MI, UMC, TCT clinical scores obtained in the pre- and post- treatment measures. The other parameters selected to compare the two groups of patients were:

1. the percentage ratios of the rising speeds of the sit to stand trials;
2. the number of steps in the walking test;
3. the speed of execution in the walking test.

Comparisons were separately executed for pre and post treatment sessions.

To all of them the U-Mann Whitney test was performed, after verifying that their distributions were not normal, according to the Kolmogorov Smirnov test. The only parameter which, by definition, included a comparison between the performance in the pre and post sessions is the ΔMVC obtained as the difference of the force computed between the post and pre treatment tests. Also ΔMVC was not normally distributed and U-Mann Whitney test was used to evaluate the differences between FES and control patients.

Results

In this study the results obtained by 20 patients (10 of FES group and 10 of control group) are reported.

FES cycling treatment

Figure 1 shows an example of the performance obtained by one patient during the FES cycling trials. In particular, the figure reports the median value of the minimum and maximum active PO computed

TABLE III.—*Comparison of the two groups in terms of the sit to stand trials.*

	# pnt done	# pnt slow ok	# pnt fast ok	# pnt speed ok	Speed slow/speed self-selected				Speed fast/speed self-selected			
					Median	25th perc	75th perc	P value	Median	25th perc	75th perc	P value
F pre	5	3	4	2	80.4	68.9	115.2	>0.05	222.0	128.4	225.6	>0.05
C pre	8	5	4	2	80.3	37.2	130.4		92.9	63.8	149.2	
F post	10	9	8	7	53.2	44.4	78.8	0.02*	148.9	114.5	173.2	>0.05
C post	9	3	4	0	119.7	73.0	174.2		104.5	74.3	324.8	

Comparison of the two groups in terms of the results of the sit to stand trials. *The U-Mann-Whitney test showed a significant difference between the percentage ratio obtained by the two groups (P=0.05).

in a semi-revolution in each minute of trial obtained in the first day (Figure 1A) and in the last day of treatment (Figure 1B).

As it is shown in Figure 1, in the first day of treatment it is very difficult to distinguish the FES phase from the passive one. Instead, in the last day there was a great increase in the active PO reaching a maximum of 19W when the healthy leg was pushing and a maximum of 17W when the impaired leg was pushing.

Figure 2 shows the results of the U-Mann-Whitney test performed on the minimum and maximum of the active PO obtained in each half revolution for the whole group.

The increase in the maximum and minimum active PO obtained between the first and the last day was always significant (P<0.05).

Comparison between the control and the FES cycling group

To verify whether the FES cycling was an efficient rehabilitation method, the results of the pre- and post-treatment tests performed on the two groups were compared.

Table II reports the clinical scores obtained by each patient of the two groups.

Controls and FES subjects were comparable with respect to demographic and clinical data before treatment (Table I,II). At the end of the rehabilitation the two groups remained comparable in terms of MI UMC and TCT. Indeed the U-Mann-Whitney test did not show any significant difference between the control and FES group both in the initial and final tests.

As it is shown in Table III, before the treatment 5 patients of the FES group and 8 of the control group performed the sit to stand task while after the treatment only 1 control patient did not recover the ability to carry out the movement. In the beginning 2 patients per each group performed the motor task managing properly the operator request on the speed of execution. It is noteworthy that after treatment 7 FES patients recovered completely their motor control while no one in the control group was able to perform both the slow task with a rising speed lower than the 90% of the self-selected speed and the fast task with a rising speed greater than the self-selected one. The U-Mann-Whitney statistical test showed that in the pre-treatment tests the two groups did not produce any significant difference in the rising speeds. On the contrary, after treatment the two groups were significantly different in the percentage ratio of the rising speed computed between the slow and the self-selected trial after treatment (P=0.02). The percentage ratio computed between the fast and self-selected speed did not show any significant difference between the two groups because the number of control patients with an acceptable ratio (>110%) was very small and two of them produced a percentage ratio greater than 400%

Figure 3 shows the statistical results obtained analyzing the Δ MVC produced by the paretic and healthy leg.

For both the legs the FES group showed a significantly greater median value of ΔMVC with respect to the control group (P<0.05 for the ΔMVC produced by both the paretic and healthy leg).

Considering the walking test, at the beginning only two patients of both the groups were able to perform the trial for a distance of 50 m (Table IV). On the contrary, at the end of treatment all FES patients reached the indoor movement ability while the 20% of the control patients remained still unable to walk for 50 m. The U-Mann-Whitney test did not show a significant difference between the number of steps and the walking speed obtained by the two groups.

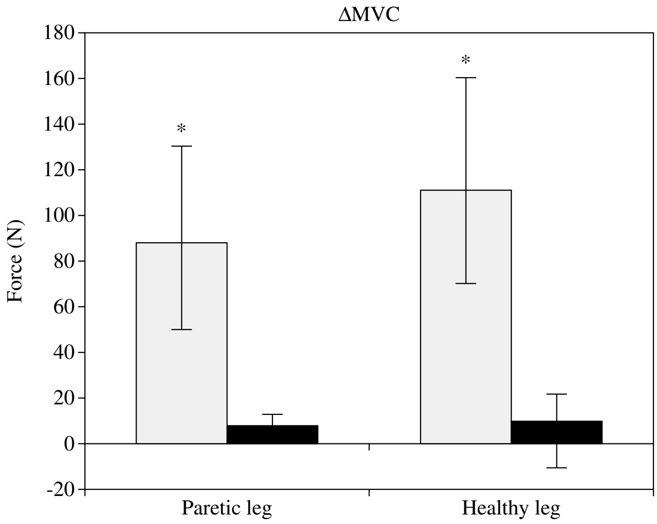

Figure 3.—Results obtained during the MVC trials in terms of the median and quartiles of the ΔMVC. The results of the paretic legs and healthy legs are reported. The white bars represent the FES group and the black ones the control group. The asterisks indicate when the forces obtained by the two groups are significantly different.

Discussion

In this study an FES cycling protocol was defined and used as a rehabilitation treatment to use on individuals with stroke in addition to the SR.

This exercise, already studied and used in individuals with spinal cord injury,[19-21] provides a large number of therapeutic and medical benefits:[22-25] increase in strength, endurance and mass of paralyzed muscles,[26] improvement of cardiopulmonary fitness,[27-29] raise of the lower limb circulation,[29] decrease in the loss of bone mineral [30] and increase in the range of joint motion.[23] The possibility of using a rhythmic, cycling and bilateral movement such as cycling induced by symmetrical stimulation pattern delivered in both legs seems to be a good rehabilitative method for post-acute stroke patients. These patients, having an unilateral motor impairment, need to be re-educated to the correct use of both the lower limbs together in order to recover the motor control symmetry in more complex and demanding tasks, such as walking.

The results obtained during the FES cycling treatment showed a significant increase in the active PO produced. The increase of the maximum value of active PO, noticeable in Figure 1, implies that there was an increase in the strength of the muscles involved in pedaling. In the last day the active PO produced in the stimulation phases was always grater than 0. This means that the patient had completely learnt to let the stimulation mastering his cycling without contrasting it, differently from the first day. This improvement implies that the patient learned the neuro-motor control mechanisms of FES cycling properly. In the last day the value of the white and black bars in each minute of trial were quite similar; this could imply that the patient was performing a symmetrical task. The treatment effect resulted repeatable in all the FES group, indeed, the active PO produced the last day was significantly greater than the one produced in the first day ($P<0.05$).

The comparison of the two groups showed that the FES group produced a significantly higher increase of the muscular strength (Figure 3, $P<0.05$): the patients of the FES group generated a Δ MVC force that was 10 times greater than the one obtained by patients of the control group. Therefore, this benefit of FES cycling, already demonstrated for spinal cord patients,[26] is still valid for stroke patients.

The FES cycling treatment had a strong impact on the motor recovery; indeed all the patients of the FES group recovered the ability to perform the sit to stand trial and in particular to discriminate between different speed of execution of the task. All the patients of

TABLE IV.—*Results of the walking test of 50 m on the two groups.*

	# pnt done	# steps				Speed (m/s)			
		Median	25th perc	75th perc	P value	Median	25th perc	75th perc	P value
C pre	2	84	55	57	>0.05	0.403	0.402	0.405	>0.05
F pre	2	56	74	94		0.295	0.252	0.337	
C post	10	76	65.5	88.8	>0.05	0.357	0.213	0.588	>0.05
F post	8	79	72.5	89.5		0.305	0.254	0.330	

The results of the walking tests obtained by the two groups in terms of number of steps and speed of execution are reported.

the control group instead remained still unable to do it after 4 weeks of SR. The statistical comparison between the two groups demonstrated that the percentage ratio between the slow and the self-selected rising speed obtained for the FES patients was significantly better than the one obtained by the control group (P=0.02).

These are only the results obtained comparing 20 subjects well matched in age and time elapsed from the ictus. It will be necessary to enlarge the number of patients in the two groups in order to let these preliminary results become general findings on the efficacy of the FES cycling treatment.

It will be interesting to analyse the long term effect of the FES cycling treatment. This could be carried out repeating the pre- and post- treatment tests also 6 months after the end of the rehabilitation of all the patients.

In this study, during the treatment the symmetry of the cycling movement was taken for granted by giving a stimulation strategy which was exactly the same for both the legs (there was only an angular shift of 180° between the muscular stimulation ranges of the two legs) and the patient was asked not to voluntary contribute to the motor task. But, if the two legs were acting differently because of a different reaction to the stimulation parameters or a diverse effect of fatigue in the two sides, there was not the possibility to adjust the stimulation parameters in order to compensate the problem and to improve symmetry. A possible advance, already ongoing in our laboratory, would be the design of an automatic controller able to assure symmetry analysing proper signals coming from both the pedals independently.

Conclusions

A further development would be the analysis of the reorganization of the cerebral cortex considering both the medium and long term recovery will be very useful to understand the real benefits of the treatment.

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