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A novel biofeedback cycling training to improve gait symmetry in stroke patients: a case series study

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Abstract— **The restoration of walking ability is crucial for maximizing independent mobility among patients with stroke. Leg cycling is becoming an established intervention to supplement ambulation training for stroke patients with problems of unbalance and weakness. The aim of the study was to explore the feasibility of a biofeedback pedaling treatment and its effects on cycling and walking ability in chronic stroke patients. Three patients were included in the study. The training consisted of a 2-week treatment of 6 sessions, during which a visual biofeedback helped the participants in maintaining a symmetrical pedaling. Participants were assessed before, after training and at follow-up, by means of a pedaling test and gait analysis. Outcome measurements were the unbalance during pedaling, the temporal, spatial and symmetry parameters during walking. An intra-subject statistical analysis (ANOVA, $p<0.05$) showed that all patients significantly decreased pedaling unbalance after treatment and maintained the improvements at follow-up. The training induced some gait pattern modifications in two patients: one significantly improved mean velocity and gait symmetry, while the other one reduced the compensation strategy of the healthy leg. The results demonstrated the feasibility of the treatment. If further trials on a larger and controlled scale confirmed the same results, this treatment, thanks to its safety and low price, could have a significant impact as a home-rehabilitation treatment.**

Stroke rehabilitation; biofeedback; pedaling; gait symmetry

I. INTRODUCTION

Stroke is the leading cause of acquired adult disability [1]. The most common and widely recognized deficit caused by stroke is hemiparesis, a motor impairment which typically affects one side of the body, contralateral to the brain hemisphere where the lesion occurs. Clinical studies on central motor neuroplasticity support the role of goal-oriented, active, repetitive movements in the training of the paretic limb to enhance motor relearning and recovery [2].

The recovery of walking is the most important objective in the post-stroke lower limb rehabilitation, with gait speed regarded as a sensible and reliable marker of deficit severity and functional walking ability [3]. Because of the laterality of the motor impairment, promoting a symmetrical gait pattern is important for maximizing independent mobility among stroke patients. Thus, gait speed together with gait symmetry indices are crucial functional indicators of an improved walking ability [3,4].

However, effective interventions for gait training are limited because extensive assistance is required for individuals with unstable balance, muscle weakness, and a persistent deficit in movement coordination. Therefore, leg cycling training is becoming an established intervention to supplement functional ambulation training [5]. Cycling shows a kinematic pattern similar to the one of walking: both tasks are cyclical, require reciprocal flexion and extension movements of hip, knee and ankle, and have alternating activation of agonist/antagonist muscles in a well-timed and coordinated manner. Furthermore, cycling can be safely performed even from a wheelchair avoiding problems of balance. This makes pedaling a safer and more economic intervention compared to gait training, suitable to be performed by chronic patients also at home, without the constant supervision of a therapist. Despite the safety of the cycling exercise, not optimal cycling solutions could be adopted by stroke patients. Indeed, since the two legs are simultaneously acting on a single crank, it is possible that the non-paretic leg completely compensates for the paretic one [6]. This pedaling strategy can result in an effective pedaling in terms of speed and total power output, but it can produce a strong cycling unbalance limiting the possible benefits and even worsening the gait performance.

Providing an online feedback about patients' performance during training improves patients motivation, allows the therapists to assess the exercise and may lead to an enhancement in the motor relearning process [7]. This rehabilitative method is well known with the term of biofeedback (BF). The use of BF re-endows patients with sensorimotor impairments with the ability to assess physiological responses and possibly to relearn self-control of those responses [8]. Besides, continued training could establish new sensory engrams and help patients to perform tasks without feedback [9]. To maximize the effect of BF it may be important to apply it within task-oriented activity and with a feedback mode that facilitates motor relearning [8].

Since the recovery of symmetrical movements is crucial in the rehabilitation of stroke patients [10] in our laboratory a cycle-ergometer was instrumented to measure the torque values produced at the right and left crank arms during pedaling [11]. Starting from this setup, an information fusion algorithm was implemented in order to visually display to the patients an intuitive index strictly correlated with the symmetrical involvement of the two legs in terms of torques provided at the crank arms during pedaling. The aim of the present study was to develop a BF controller and to evaluate its feasibility and clinical efficacy as a rehabilitation treatment for chronic stroke patients. The hypothesis was that a 2-week BF cycling treatment might induce some improvements not only in pedaling performance but also in walking ability both in terms of gait speed and kinematic symmetry indices.

II. METHODS

A. *Participants*

Participants satisfied the following inclusion criteria: left or right hemiparesis following ischemic or hemorrhagic stroke, time since stroke of at least 12 months, low spasticity level for all lower limb muscles (Modified Ashworth Scale $\leqslant 2$), able to sit up to 30 minutes, joint mobility ranges that would not preclude pedaling. The only exclusion criteria was an insufficient cognitive capacity to participate in the program, including receptive dysphasia. Patients were selected in order to differ from each other in terms of gait speed and symmetry kinematic indices.

A group of 12 healthy subjects (age 22.6 years ± 3.3, height 171.8 cm ± 9.7 cm, weight 63.3 kg ± 8.9 kg) participated in the study in order to compute the normality ranges for all the outcome measurements used to evaluate the motor recovery induced on the patients by the training.

B. *Experimental Setup*

The THERA-live^{TM} (Medica Medizintechnik GmbH, Germany) motorized cycle-ergometer was chosen for the treatment. In a previous study [11], this ergometer was equipped with a shaft encoder for the acquisition of the crank angle and with strain gauges attached on the crank arms to measure the torque produced by each leg during pedaling. During training, patients sat on a chair or a wheelchair in front of the ergometer and their legs were stabilized by two foot orthoses fixed to the pedals.

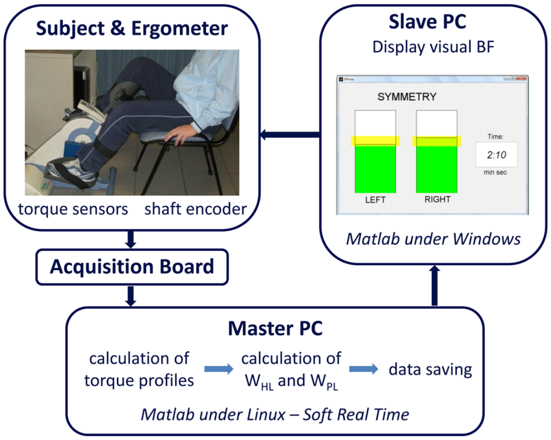

Figure 1. Experimental setup used for the intervention.

A master PC, running Matlab/Simulink® under Linux, acquired all signals coming from the ergometer with a sampling frequency of 200 Hz and calculated, at the end of each revolution, the BF indices. Then, these indices were sent to a slave PC, which provided the visual biofeedback to the patients, by displaying the BF indices through a graphical interface implemented in Matlab. The communication between the two PCs was obtained through a LAN connection using the UDP/IP protocol. The experimental setup is shown in Fig. 1.

C. *Intervention*

The treatment was performed 3 days a week for two weeks for a total of 6 sessions. Each session lasted 10 minutes: 1 minute of passive cycling, 8 minutes of voluntary cycling with visual biofeedback, and 1 minute of passive cycling. Passive cycling was guaranteed by a motor inside the ergometer which maintained the speed at a constant value of 30 rpm.

To compute the BF indices, the right and left active torque profiles as function of the crank angle were obtained by subtracting the mean torque computed during passive cycling from the torque profile calculated during each revolution of voluntary pedaling. Then, the BF indices for each revolution were computed as the net mechanical work value produced by the paretic (W_{PL}) and healthy leg (W_{HL}):

$$W_{iL} = \int_{0^\circ}^{360^\circ} T_{iL}(\theta) d\theta \, , i = \{P, H\} \tag{1}$$

where T_{iL} is the active torque profile produced at the crank arm by each leg, while θ represents the crank angle.

The slave PC displayed in real-time, at the end of each revolution, the work values produced by the two legs, through a graphical interface (Fig. 1), consisting of two bars with a height proportional to the work values and a yellow band indicating the target. Patients were asked to voluntary compensate a potential unbalance by producing with each leg a value of work within the target band. When the two work values were both within the yellow band, the bars became green, otherwise they were red. To make the exercise more challenging, the target increased when the subjects were able to fulfill the goal for at least 7 over 10 consecutive revolutions. If the patients failed to maintain the increased target for 1 minute, the target decreased again not to discourage him. The initial value of the target was fixed on each subject during a preliminary test consisting of a 30-second period of passive cycling and a 30-second period of voluntary cycling, asking the patients to pedal with maximal effort. At the end of this test, the work values for each revolution were computed and the maximal value achieved by the paretic leg (W_{PLmax}) was used to set the target interval between a minimal value of 80% W_{PLmax} ± 10% W_{PLmax} and a maximal value of 120% W_{PLmax} ± 10% W_{PLmax}.

The proposed protocol was approved by the Ethical Committee of the rehabilitation center and each participant signed an informed consent.

D. *Assessment*

Participants were tested before training, after training, and in a follow-up assessment one week after the end of the treatment by means of the following assessment tests:

- a *pedaling test*, which comprised a 1-minute period of passive cycling and a 2-minute period of voluntary cycling. The same ergometer used for the treatment was employed for this test. Thus, the crank angle and the torque values produced at the right and left crank arms were measured and sampled at 200 Hz.
- a walking test on a 10-meter walkway. Patients were asked to walk without the shoes at a self-selected speed. No constraints were imposed to the subjects and neither assistive devices were used during the test. Three-dimensional kinematics of the subjects' lower limbs were recorded with the Elite clinic™ (BTS, Milano, Italy) motion analysis system (8 cameras, sample rate 100 Hz) using the SAFLo protocol [12]. Ground reaction forces were measured with two dynamometric force platforms (Kistler, Winterthur, Switzerland).

E. *Data Analysis and Statistics*

The performance achieved daily during the treatment was evaluated by means of the ratio between the number of symmetrical revolutions and the total number of revolutions (BF_{perf}).

The outcome measurements achieved during the pedaling test were the values of W_{HL}, W_{PL}, and the pedaling unbalance, U, computed as:

$$U = \frac{|W_{HL} - W_{PL}|}{(|W_{HL}| + |W_{PL}|)} \qquad (2)$$

U could range from 0 (two identical works) to 100 (W_{PL} negative or equal to zero).

All raw data acquired during the walking test were filtered with a fifth order Butterworth filter (cutoff frequency of 5 Hz) and elaborated to compute kinematics, kinetics and standard temporal and spatial gait parameters [12]. To evaluate gait symmetry two parameters were computed:

- ST ratio, i.e., the ratio between stance time in percentage of stride time obtained by the paretic leg and the one obtained by the healthy one. The ST ratio could be related to balance control issues and reflect the patients' trends to shorten the paretic stance time [4].
- SV ratio, i.e., the ratio between the swing velocity obtained by the paretic leg and the one obtained by the healthy one. The SV ratio could be related to an insufficient power generated to swing the paretic limb quickly and to an increased time for the paretic foot placement [4].

All values of the temporal and spatial gait parameters reported were the mean values of 4 to 5 repeated gait trials along the walkway at the preferred speed.

An intra-subject one way Analysis of Variance (ANOVA, $p < 0.05$) was performed on all outcome measurements to identify any difference between pre-training, post-training, and follow-up assessments. Moreover, the values of pedaling unbalance and all gait parameters obtained by the patients in each assessment test were compared to the results achieved by the group of healthy subjects. A t-test was employed to verify statistical differences between patients and able-bodied subjects ($p < 0.05$).

III. RESULTS

A. *Participants*

After giving their informed consent, 3 chronic stroke subjects, were included in the case series study. Patients details are reported in Table 1.

TABLE I. PARTECIPANTS' BASELINE DETAILS

Case	Age (years)	Gender	Etiology	Years since stroke	Affected Side	MAS (0-4)
S1	23	F	I	1	L	1
S2	51	M	I	10	R	1
S3	27	M	H	9	R	2

M=Male; F=Female; I=Ischemic stroke; H=Hemorrhagic stroke; L=Left; R=Right

B. *Intervention*

Fig. 2 depicts a comparison between the performance obtained by S3 during the first (panel (a)) and the last (panel (b)) day of treatment in terms of work values produced by the two legs during the 8-minute period of voluntary cycling with visual biofeedback.

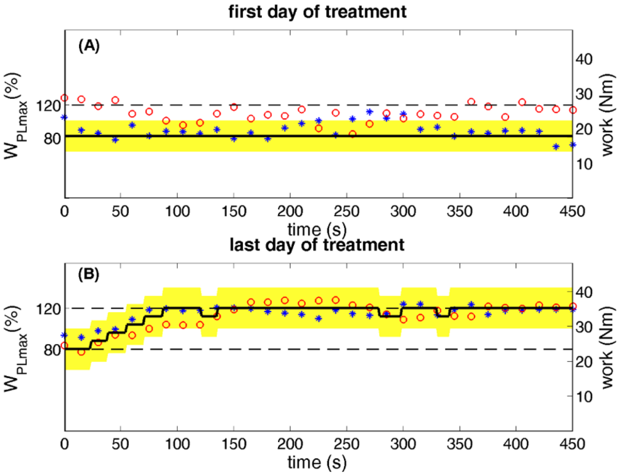

Figure 2. Results obtained by S3 in the first (panel (A)) and last (panel (B)) day of treatment. Each asterisk and circle indicate the mean values, among 10 consecutive revolutions, of the work produced by the paretic and non paretic leg, respectively. The black line shows the target value and the surrounding yellow area represents the tolerance band. In both panels, double vertical axes are used to indicate both the absolute work value and the minimal and maximal target values in percentage of W_{PLmax} allowed during the training.

In the last day of treatment S3 was able to perform and maintain a symmetric pedaling: work values produced by both paretic and non-paretic legs (asterisks and circles) were included in the tolerance area (yellow area). Indeed, the target work (black line) increased till the maximum value (120% W_{PLmax}) and was maintained for the whole period of voluntary pedaling. This result suggested us that S3 was able to understand and exploit properly the visual biofeedback in order to optimize the pedaling symmetry during training. In addition, the treatment induced an increase of force generated by S3, being the target work used in the last day of treatment double of the one adopted in the first day.

Concerning the performance achieved daily during the treatment, all patients increased the value of BF_{perf}. In particular, S1, starting from a value of 24% achieved in the first day of treatment, obtained a value of 56% in the last day; S2 started from 5% and reached a value of 15%; finally, S3 increased the performance from 10% to 74%. This result suggested us the efficacy and easiness of the visual feedback provided to the patients.

C. Normality ranges

During the pedaling test, the group of healthy subjects produced a value of unbalance equal to U = 2.43% ± 2.10%.

Table 2 reports the normality ranges obtained on the group of healthy subjects during the walking test in terms of spatio-temporal parameters and symmetry indices.

TABLE II. NORMALITY RANGES FOR THE GAIT ANALYSIS TEST

	Leg	Mean (SD)
Spatio-temporal parameters		
Stance Time [%stride]	Right	59 (1)
	Left	58 (2)
Stride length [mm]	Right	1395 (136)
	Left	1399 (128)
Swing velocity [m/s]	Right	3.28 (0.34)
	Left	3.19 (0.29)
Mean Velocity [m/s]		1.32 (0.11)
Symmetry indices		
ST ratio		0.98 (0.03)
SV ratio		0.97 (0.06)

SD indicates the standard deviation.

D. Assessment

Table 3 summarizes the results obtained by the three patients during the pedaling test, before training, after training, and at follow-up assessments. The mean and standard deviation values of the works produced by the paretic and healthy leg and of the pedaling unbalance are reported. All participants achieved a significant decrease of the unbalance after a 2-week treatment. In the follow-up assessment, all subjects maintained a significant improvement in the unbalance with respect to the pre-training evaluation. Comparing follow-up with post-training assessment, one subject (S3) maintained the results obtained after intervention, one (S1) further reduced the unbalance, and the last one (S2) increased the unbalance in comparison with the post-treatment evaluation, although his pedaling remained significantly more symmetrical than the one of the pre-treatment assessment. Looking at the mean work produced by each leg, the strategies adopted by the three patients in order to reduce the unbalance showed some differences:

- S1 mainly obtained an increase of W_{PL};
- S2 increased both works but the W_{PL} was doubled in the post-treatment evaluation with respect to the pre-training score. His performance was reduced in the follow-up assessment but a significant improvement was maintained with respect to the baseline;
- S3 reduced significantly the performance of both legs, but more the one of the healthy side.

TABLE III. RESULTS OF THE PEDALING TEST

	PRE	POST	FU	P-value
S1				
U (%)	31.5 (8.0)	24.7 (9.6)	18.3 (7.3)	<0.01*,+,§
W_{HL} (Nm)	47.8 (5.5)	45.0 (5.8)	43.3 (5.6)	<0.01*,§
W_{PL} (Nm)	25.2 (5.5)	27.4 (5.3)	30.1 (5.6)	<0.01*,+,§
S2				
U (%)	45.4 (7.8)	29.2 (13.0)	39.9 (13.7)	<0.01*,+,§
W_{HL} (Nm)	35.0 (6.5)	43.5 (12.7)	43.1 (10.3)	<0.01*,§
W_{PL} (Nm)	13.0 (2.6)	25.7 (10.9)	19.3 (7.9)	<0.01*,+,§
S3				
U (%)	38.1 (9.4)	12.4 (10.1)	13.6 (10.6)	<0.01*,§
W_{HL} (Nm)	78.5 (8.3)	36.2 (4.3)	42.8 (3.9)	<0.01*,+,§
W_{PL} (Nm)	35.9 (9.2)	29.3 (4.9)	33.7 (6.8)	<0.01*,+

Values: Mean (SD); P-value: Significance level of one way ANOVA - Post hoc: Scheffè; * = significant difference between PRE and POST; + = significant difference between POST and FOLLOW-UP; § = significant difference between PRE and FOLLOW-UP.

Although the treatment induced a significant improvement of the pedaling unbalance in all subjects, the t-test performed to compare patients' performance with the group of healthy subjects showed significant differences at all assessment tests (pre-training, post-training, and follow-up).

Table 4 reports the results of the gait analysis assessments for the three patients. As required by the inclusion criteria, it is noticeable that at baseline participants differed from each other both in terms of mean velocity and in terms of gait symmetry indices. In particular, S2 was characterized by a low gait speed and an asymmetrical gait pattern, S1 had a more symmetrical but still slow gait, and S3 walked faster but his pattern was unbalanced. The treatment resulted to be very beneficial in terms of walking ability recovery for S2. Indeed, the treatment produced a statistically reliable increase in the mean velocity, due to both a significant increase in the stride length and a significant decrease in the stride time for the two legs. These improvements were maintained at follow-up keeping the mean velocity significantly higher than in the pre-training assessment, even if it was lower than at post-treatment evaluation. Furthermore, S2 changed his gait pattern: he modified the step temporization producing a more symmetrical balance between the stance and swing phases and maintained this temporization in the follow-up assessment. The post-treatment assessment was also characterized by an increase of the swing velocity of the paretic leg ($p < 0.01$); this latter benefit was not maintained at follow-up. The treatment produced a significant improvement in the temporization of the gait pattern also for S3: the stance and swing time percentages with respect to the stride time significantly changed in the healthy leg (p = 0.04). This improvement corresponded to a slightly longer stride length in both paretic and healthy side. All these progresses were preserved at follow-up. Finally, the treatment did not induce any gait improvement in S1. The only significant variation in the gait parameters was an increase of the swing velocity of the healthy leg but it seemed not to be related to the treatment because the post-hoc analysis revealed that a difference existed between the pre-treatment and the follow-up assessment but not between the pre- and post-training assessments.

TABLE IV. RESULTS OF THE GAIT ANALYSIS TEST

	Leg	**PRE**	**POST**	**FU**	**P-value**
S1					
Stance Time [%stride]	P	64 (2)	63 (2)	65 (3)	0.43
	H	70 (2)	72 (2)	71 (3)	0.48
Stride length [mm]	P	859 (18)	817 (26)	845 (34)	0.29
	H	820 (25)	812 (51)	872 (40)	0.07
Swing speed [m/s]	P	1.27 (0.08)	1.28 (0.04)	1.40 (0.14)	0.11
	H	1.47 (0.05)	1.67 (0.15)	1.69 (0.13)	_0.03§_
Mean speed [m/s]		0.44 (0.03)	0.47 (0.01)	0.49 (0.03)	0.07
ST Ratio		0.92 (0.04)	0.89 (0.03)	0.92 (0.04)	0.32
SV Ratio		0.86 (0.05)	0.77 (0.09)	0.83 (0.11)	0.31
S2					
Stance Time [%stride]	P	48 (4)	54 (2)	53 (2)	_0.03*_
	H	79 (8)	69 (1)	66 (3)	_0.01*,§_
Stride length [mm]	P	637 (46)	745 (31)	630 (13)	_<0.01*,+_
	H	619 (72)	788 (37)	666 (20)	_<0.01*,+_
Swing speed [m/s]	P	0.66 (0.27)	1.12 (0.07)	0.81 (0.07)	_<0.01*,+_
	H	1.37 (0.25)	1.66 (0.14)	1.21 (0.07)	_0.01*,+_
Mean speed [m/s]		0.31 (0.04)	0.52 (0.03)	0.40 (0.01)	_<0.01*,+,§_
ST Ratio		0.57 (0.05)	0.72 (0.03)	0.83 (0.05)	_<0.01*, §_
SV Ratio		0.53 (0.14)	0.70 (0.06)	0.67 (0.03)	_0.02 *_
S3					
Stance Time [%stride]	P	57 (2)	56 (2)	55 (3)	0.38
	H	68 (3)	65 (1)	65 (2)	_0.04*_
Stride length [mm]	P	986 (30)	1016 (59)	1012 (87)	0.42
	H	1026 (19)	1053 (50)	1088 (69)	0.20
Swing speed [m/s]	P	1.82 (0.14)	1.74 (0.13)	1.73 (0.05)	0.53
	H	2.45 (0.27)	2.25 (0.16)	2.31 (0.26)	0.38
Mean speed [m/s]		0.78 (0.04)	0.78 (0.06)	0.78 (0.04)	0.93
ST Ratio		0.80 (0.04)	0.87 (0.05)	0.81 (0.07)	0.15
SV Ratio		0.75 (0.09)	0.78 (0.07)	0.76 (0.09)	0.79

P indicates the paretic leg; H the healthy one. Values: Mean (SD); P-value= Significance level of one way ANOVA $p<0.05$ - Post hoc: Scheffè; * = significant difference between PRE and POST; + = significant difference between POST and FOLLOW UP; § = significant difference between PRE and FOLLOW UP.

Table 4 reports also the results of the walking test in terms of gait symmetry. Only S2, who was the most impaired subject, reduced significantly the asymmetry after treatment in terms of both ST ratio and SV ratio; these improvements were maintained at follow-up.

Among all spatio-temporal parameters reported in Table 4, the stance and swing time of the paretic leg of S3 resulted to be always included in the normality ranges, whereas S1 resulted to be not significantly different from the healthy subjects group in terms of ST ratio and SV ratio during the pre-training and the follow-up assessment.

IV. DISCUSSION

The present work investigated the feasibility of a biofeedback cycling treatment and its effects on cycling unbalance and walking parameters in three case studies of chronic stroke patients. In our experimental approach we tried to keep to the key ingredients for motor functional recovery providing an intensive and repetitive task training able to maintain a high active involvement of the patient during the intervention [8]. Furthermore, to maximize patients' involvement we increased the task difficulty as the participants' skill improved. The results obtained on the three patients emphasized the importance of developing biofeedback treatment approaches that are effective in maximizing underlying mechanisms responsible for neurological and adaptive recovery in individuals with hemiparesis, even in chronic state. The chosen visual feedback was functional to the goal of obtaining a symmetrical pedaling and resulted simple to be understood by patients.

The most appealing questions for the proposed treatment are whether the effects obtained during the training can be maintained also when the exercise is performed without the visual BF and most of all whether the effects obtained on cycling symmetry can be translated to the walking performance. To reply to the first question, it can be noticed that in the post-treatment assessment all patients significantly reduced their pedaling unbalance with respect to baseline (Table 3). It is worthwhile underlying that the unbalance was computed between the total net mechanical works produced by the two legs. This means that an unbalance equal to zero does not necessary indicate that the torque profiles acquired at the crank arms were identical.

Concerning the second question, the treatment, even short, seems to induce some modifications on the gait kinematic pattern in two of the three chronic patients. The most significant improvement was obtained by S2. This patient was characterized by a very slow and asymmetrical gait at baseline. After treatment, he doubled the swing velocity of the paretic leg meaning that the patient started to produce the inertia to generate the step also with the paretic leg and to translate this inertia in distal propulsive force improving the kinetic both at the foot and knee (results not shown). This result is confirmed by a significant improvement of gait symmetry that was also maintained (SV ratio) or further increased (ST ratio) at follow-up. In the post-treatment assessment, S2 obtained also a significant increase in the mean velocity of the gait, that is a crucial functional indicator of an improved walking ability. His self-selected speed increased of 67% with respect to baseline, changing from 0.32 m/s to 0.51 m/s; this increase can be recognized as enough to change from a category of a household walker to a full community walker. This advance indicates a potential improvement in the quality of life following the proposed treatment [13]. This progress on walking velocity was preserved in the follow-up assessment even if at lower levels, implying that a 2-week treatment was not enough to induce permanent changes in the walking ability of S2. The treatment produced some benefits also in the gait pattern of S3, who at baseline exhibited gait asymmetry due to an overuse of the healthy limb. He obtained a significant improvement in the alternation of stance and swing phases of the healthy leg, reducing the compensation strategy used during walking. This behavior was exactly the same he adopted also to reduce the pedaling unbalance. For this patient, the improvements induced by the treatment were maintained one week after the end of the treatment. However, the significant benefits obtained in the symmetry of pedaling were not translated into significant improvements in the gait symmetry even if a slight increase of symmetry was obtained after treatment (Table 4). Finally, S1 did not change her gait pattern after only 2 weeks of treatment and maintained her slow but safe and almost symmetrical gait mostly due to a general ipotonia. Probably a treatment focused on the recovery of symmetry was not useful for a patient that was characterized by gait symmetry parameters included in the normality ranges before treatment.

Our preliminary results suggest that an intensive treatment of only 6 days is able to induce improvements in terms of pedaling unbalance and, sometimes, also in terms of walking ability but probably a more prolonged treatment would be more effective in translating progresses from pedaling performance into locomotor capability and in maintaining the results over time. Naturally, the duration of the treatment has to be optimized depending on the specific patient condition in strict collaboration with physicians. This study tries also to give some suggestions about how to choose patient categories which can avail themselves of the treatment. The treatment seems to be beneficial for people with a very asymmetrical and inefficient gait, such as S2, and for people that make an overuse of the healthy leg to compensate for their asymmetry, like S3.

Certainly a more robust statistical study (e.g. randomized controlled trial) is required to provide a clear evidence that a biofeedback pedaling treatment significantly improves walking ability in chronic stroke patients. To validate the carry-over effect from pedaling to overground locomotion a more prolonged treatment (e.g. a 4-week intervention) will be tested on a targeted category of individuals with stroke, i.e., patients characterized by a very asymmetrical and slow gait. If the effect is demonstrated on a larger and controlled scale, the proposed intervention, thanks to its safety and low price, could really have an impact also as a home-rehabilitation treatment for chronic stroke patients.

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