Available online at www.sciencedirect.com

ScienceDirect

Clinical Biomechanics 23 (2008) 1086–1094

CLINICAL BIOMECHANICS

www.elsevier.com/locate/clinbiomech

Functional electrical stimulation assisted cycling of patients with subacute stroke: Kinetic and kinematic analysis

J. Szecsi [a,b,*], C. Krewer [a], F. Müller [a], A. Straube [b]

[a] Neurologische Klinik, Bad Aibling, Germany

[b] Center for Sensorimotor Research, Department of Neurology, Ludwig-Maximillians University, Marchioninistrasse 23, 81377 Munich, Germany

Received 14 January 2008; accepted 2 May 2008

Abstract

Background. Cycling is a safe and functionally effective exercise for patients with early post-stroke and poor balance. Such exercise is considered even more effective when functional electrical stimulation is added.

Our principal aim was to determine the biomechanically quantifiable parameters of cycling that can be improved in patients with subacute hemiparesis by incorporating functional electrical stimulation. These parameters were defined as objective goals that can be achieved in clinical applications. A secondary aim was to determine whether they could be used to identify subjects who would benefit from such therapy.

Methods. Using a tricycle testbed, we tested 39 subacute (mean 10.9 weeks post-stroke (SD 5.9)), hemiplegic subjects. During isometric measurements we recorded volitional and electrically evoked crank torques, the latter at maximal tolerable intensity. During ergometric measurements, volitional pedaling was alternated with combined pedaling (volitional supported by stimulation), performed at 30-s intervals. Power, smoothness, and symmetry of cycling were evaluated.

Findings. Twenty-six percent of the subjects significantly improved the smoothness of their cycling with functional electrical stimulation. Only 8% and 10% significantly increased their power and symmetry, respectively. The improvement in smoothness significantly correlated with the capability of the individual to generate electrical torque (Spearman's rank correlation coefficient = 0.66 at $P = 0.001$).

Interpretation. The smoothness of cycling was the most sensitive parameter improved by functional electrical stimulation. This improvement depended on the amount of torque evoked, and the torque achieved, in turn, correlated with the tolerated intensity of stimulation.

Keywords: Hemiparesis; FES cycling; Smoothness; Pedaling; Isometric torque; Stimulation intensity

1. Introduction

Survivors of strokes or cerebrovascular accidents often have physical impairments that greatly affect their daily life activities (Bobath, 1994). The most important of these disabilities is probably the loss of ambulation (Zorowitz, 2006). The prerequisites of ambulation are adequate muscle strength to stabilize the hip and knee joints, and adequate trunk control to sit and stand.

Post-stroke patients suffer from postural imbalance or asymmetric limb movements (Brown and Kautz, 1999), which are caused by inappropriate contractions of the agonist and antagonist muscles, weakness, spasticity, or abnormal synergistic patterns. Besides generating less mechanical power, their asymmetric limb movements preclude performance of smooth and symmetrical movements of the legs, which are typical in normal walking or cycling. While it is essential to restore ambulation in these patients, very few of them can participate in gait training immediately after

* Corresponding author. Address: Center for Sensorimotor Research, Department of Neurology, Ludwig-Maximillians University, Marchioninistrasse 23, 81377 Munich, Germany.

E-mail address: jszecsi@nefo.med.uni-muenchen.de (J. Szecsi).

0268-0033/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.clinbiomech.2008.05.001

stroke (Hwang et al., 2003), for they have lost the ability to stand upright and step symmetrically.

Cycling gives these patients the opportunity to relearn timing accuracy and to develop adequate reciprocal force required for locomotion, because it is similar to reciprocal stepping (Brown and Kautz, 1998). It also has the clinically relevant physiological benefits of aerobic exercise: it improves maximal oxygen consumption, workload and endurance, as well as lowers systolic blood pressure (Giuliani et al., 1989; Potempa et al., 1995). A high-exertional pedaling program would also be expected to counteract muscle atrophy and disuse (McComas et al., 1973; Dietz et al., 1986; Hachisuka et al., 1997), and to result in chronic strength gain (Brown and Kautz, 1998). Moreover, since cycling is practiced in a sitting position, it is a safe and functionally effective exercise for these patients, who have a wide range of motor impairments including poor balance (Brown et al., 1997; Rosecrance and Giuliani, 1991).

Functional electrical stimulation (FES) can be combined with cycling (Chen et al., 2005) in a treatment protocol that aims to generate the active movement of paralyzed muscles. The use of an FES approach in the early phase of stroke rehabilitation facilitates the achievement of better functional output in a shorter period of time (Malezic et al., 1987; Kralj et al., 1993). So far neither the therapeutic effect of FES coupled with cycling in patients with subacute stroke is known, nor have the biomechanical parameters that could be improved by such therapy been investigated.

In patients with chronic hemiparesis who retain the ability to stand and walk, the main outcome measures that can be improved with FES are walking speed, cadence and the physiological cost index (Malezic et al., 1994; Burridge et al., 1997). Similarly one would expect that those biomechanical parameters primarily related to pedaling would improve with FES-supported cycling of hemiparetic subjects.

The advantages of FES-propelled cycling for persons with complete spinal cord injury (SCI) are like those of cardiovascular training (Glenn and Phelps, 1985; Glaser, 1994), muscle-strengthening exercises (Mohr et al., 1997), and cycling-mobility improvements (Perkins et al., 2002; Hunt et al., 2004). All are strongly related to the generated mechanical output power.

The enhancement of mechanical power is, however, not directly applicable to the cycling of patients with hemiparesis, because FES cycling in these patients differs in the three following ways:

(1) The intensity of the superficial electrical stimulation of the muscles has to be limited, because the patients have partially preserved sensibility, hyper-sensibility or even post-stroke central-pain syndrome (Zorowitz, 2006).
(2) Since patients with stroke often still have considerable strength, they can in most cases engage in volitional cycling even without supporting FES.
(3) These patients have asymmetrical movement patterns due to unilateral muscle weakness or spasticity.

The principal aim of this study was to determine the quantifiable biomechanical parameters of cycling which FES can improve in patients with subacute hemiparesis. These parameters can therefore be defined as objective goals for the clinical application of FES-supported cycling therapy. For this purpose, kinetic and kinematic parameters of cycling (isometric torque, output power, as well as the recently proposed smoothness of movement and symmetry of forces) (Chen et al., 2005) were compared under conditions of volitional and FES-elicited contraction.

A second goal was to explain why patients with hemiparesis are able to improve their kinematic and kinetic parameters of cycling with the support of FES. We hypothesized that kinetic or kinematic improvements depend primarily on the patient's ability to generate electrically evoked torques. This ability could in turn depend on (1) the pain threshold of the subject (defined as maximal tolerated stimulation current intensity) or (2) the volitional torque-generating capability on the affected or unaffected side of the subject (as an indicator of the recruitable muscle mass).

2. Methods

2.1. Subjects

Thirty-nine subjects (15F/24M; age: mean 68.7 years (SD 10.9)) with subacute hemiparesis (mean 10.9 weeks post-stroke (SD 5.9)) took part in the study. Table 1 summarizes the clinical data and the functional assessments of the study participants. The subjects with hemiplegia were severely disabled (Barthel Index mean 28.1 (SD 19.0)): their mobility ranged from greatly impaired to confined to a wheelchair (functional ambulation category mean 0.8 (SD 1.1)). Most of these subjects were not able to stand independently, and therefore treadmill therapy was considered un-suitable (Malezic and Hesse, 1995). All had moderately increased muscle tone during knee extension (Modified Ashworth Scale mean 1.2 (SD 1.1)). Sensibility was preserved; however, it was reduced or disturbed in all but one subject, who was completely anesthetic. The subjects were able to comprehend simple commands. The University of Munich ethics committee approved the study, and the subjects gave their informed consent prior to participation.

2.2. Study design

Each participant in this cross-sectional study underwent first a static and then a dynamic measurement during one experimental session.

2.3. Stimulation

The quadriceps and hamstrings muscle groups of the affected side were electrically stimulated during ergometric

Table 1
Study participants

ID	Age	Gender	Time since stroke (w)	Paretic side	Standing coordination	Functional ambulation classification (5)	Barthel-Index (100)	Sensibility LE: touch, pain, vibration	Modified Ashworth Scale
1	61	m	5	R	FU	1	15	(-)(-)(-)	1+
2	74	m	24	R	n.m.	0	55	n.m.	1
3	79	m	4	R	SS	0	20	(x)(x)(—)	1
4	77	f	8	L	FU	1	40	(x)(x)(x)	1
5	73	f	14	L	SS	0	50	(–)(-)(–)	0
6	74	m	8	R	FU	0	30	(-)(-)(-)	3
7	48	f	4	R	SS	1	42	(-)(-)(-)	1
8	63	m	12	L	SS	1	30	(-)(-)(-)	1
9	77	m	12	R	SS	1	15	(x)(x)(-)	1
10	78	m	9	L	FU	2	25	(-)(x)(-)	1
11	54	f	13	R	FS	2	65	n.m.	1
12	53	m	7	R	FU	2	50	(-)(-)(-)	1+
13	78	f	5	L	n.m.	0	15	(o)(o)(o)	1+
14	78	m	8	L	FU	1	40	(—)(—)(—)	1
15	71	m	11	R	SS	0	25	(x)(x)(x)	0
16	57	m	9	L	FU	0	30	(—)(—)(–)	2
17	56	m	14	L	n.m.	0	5	(-)(-)(-)	3
18	76	m	16	R	FU	2	30	(—)(—)(–)	2
19	76	m	12	R	SU	0	5	(—)(–)(—)	2
20	71	m	11	L	FU	1	20	(-)(–)(—)	0
21	89	f	24	R	SU	1	40	(x)(x)(-)	0
22	77	m	5	L	FS	1	35	(?)(x)(–)	1
23	60	f	4	L	SU	0	5	(x)(x)(–)	1+
24	60	f	9	L	n.m.	0	30	(–)(-)(–)	0
25	74	f	4	R	SU	0	30	(-)(-)(-)	1
26	81	m	19	L	n.m.	0	0	(-)(-)(-)	1+
27	78	m	24	L	n.m.	0	20	(-)(-)(-)	0
28	60	m	12	L	SU	1	35	(-)(—)(?)	2
29	81	f	12	R	n.m.	0	0	n.m.	4
30	72	f	7	L	FS	3	25	(x)(x)(-)	1
31	71	f	6	L	FU	0	15	(x)(x)(-)	1
32	50	f	5	R	n.m.	0	5	(-)(-)(o)	1+
33	61	m	11	R	FS	4	65	(-)(x)(—)	1+
34	73	m	11	L	SU	0	5	(–)(-)(?)	1+
35	72	m	4	R	SS	n.m.	40	(x)(x)(x)	1
36	76	f	14	L	SS	1	10	(-)(-)(—)	0
37	67	m	25	R	SU	0	35	n.m.	n.m.
38	69	m	11	R	FS	3	55	(x)(x)(-)	1
39	41	f	6	R	FU	0	40	(x)(-)(–)	0

Abbreviations: m, male; f, female; LE, low extremity; (x) normal; (-) moderately reduced; (–) strongly reduced; (0) nonexistent; (?) undetermined; n.m., not measured; FS: free standing is stable; FU: free standing is unstable; SU: supported standing is unstable; SS: supported standing is stable.

cycling. For isometric measurements only the affected quadriceps group was stimulated. Although important for walking, the glutei muscle group and also muscles of the contralateral, non-affected side were not stimulated for practical reasons. Pairs of autoadhesive gel electrodes (Flextrode, Krauth + Timmermann Ltd., Hamburg, Germany) (size, 4.5×9.5 cm^2) were placed on the skin over the proximal and distal fourth of each muscle bulk. A constant current 8-channel stimulator (Motionstim, Krauth + Timmermann Ltd., Hamburg, Germany) provided the stimulation current (rectangular, biphasic, charged balanced pulses; frequency 20 Hz; maximum pulse amplitude, 127 mA; constant pulse width, 300 μs). These parameters are similar to those used in FES cycling of subjects with complete paraplegia (Szecsi et al., 2007b; Perkins et al., 2001), and so far no electrical stimulation paradigm has proven superior to it for FES cycling of subjects with incomplete paraplegia and preserved sensibility (Szecsi et al., 2007a).

During the isometric measurements and ergometric cycling the stimulator was controlled from a laptop computer by serial communication. It directed the muscle stimulator to induce muscle contractions on the affected side during cycling at the appropriate crank angles (Perkins et al., 2002) so as to support volitional pedaling (see Appendix A). Although some researchers believe that low-intensity stimulation increases voluntary strength during long-time FES training (Pape et al., 1990), the majority do not (Glinsky et al., 2007). Therefore maximal stimulation intensity, adjusted to each individual's maximal tolerance, was used in both isometric and ergometric tests.

2.4. Isometric measurements

A stationary tricycle served as testbed for isometric torque measurements. Tangential forces applied by the cyclist to the crank arms were collected from both sides using instrumented crank arms (o-tec Ltd. Kraft- und Leistungssysteme, Bensheim, Germany). The force sensors were calibrated with 20.6, 31.7 and 63.4 N weights. The nominal force amounted to 1 kN, and accuracy was 1 N, corresponding to crank torques of 0.15 N m (using 0.15-m crank arms). An 8-bit incremental encoder (accuracy 1.4°), synchronized to turn with the crankshaft, determined the actual position of the crank. Angular and force data were read in by the laptop at a sample rate of 20 Hz. The ankle joint was immobilized at 90°, and leg movement was restricted to the sagittal plane using shank and foot orthoses.

Maximal volitional knee extension force was measured for both legs. Only the maximum of electrically evoked force generated by the quadriceps group for the affected side was considered. The crank angle was set manually by fixing the crank at the desired angle with a bolt. Volitionally or electrically evoked maximal isometric torques of the left leg were expected to be at around 100° crank angle, referred to the zero degree defined by the left, backward-pointing crank arm (280° for the right leg, by considering a shift of 180°). The maximum of the torques at the crank angles 75°, 100° and 125° for the left leg was recorded (the corresponding values for the right leg were 255°, 280° and 305°). First, maximal volitional isometric torque was generated at fixed crank angular position, and the peak was noted. Then while the subject was instructed to relax, the stimulation intensity was gradually increased in steps of 5 mA until the maximal tolerated intensity (indicated by each individual) was reached. The peak electrical torque and the corresponding current intensity were recorded. Mean values over three measurements of peak torques and the corresponding stimulation intensities were calculated.

2.5. Ergometric measurements

Dynamic measurements were performed on a stationary tricycle testbed with freely turning crank and also an electromagnetic brake (TACX 1680, TACX Ltd., BW Wassenaar, Holland) attached to the left rear wheel. The breaking torque on the crank measured by the pedal sensors ranged from 0.15 N m to 7.30 N m. It was set individually at the maximal magnitude (Chen et al., 2005) at which the patient could cycle 10 min at a cadence of 40–80 rpm. Pedaling lasted a total of 10 min; the patients tolerated this period well without becoming to exhausted. After practicing volitional cycling for 2 min to get used to it, the subjects performed volitional cycling (30 s) in alternation with electrically supported cycling (30 s) for the next 8 min. Thus, eight 15-s periods (only the last 15 s of each 30-s period) were recorded for each individual and for each condition (stimulated and non-stimulated). The minimal, visually perceivable difference of smoothness (defined as roughness index, see below) was found to be 10. Thus, the number of eight intervals was chosen to ensure this minimally detectable difference of 10 for the intercondition comparison of smoothness (see below), at a significance of 0.05 and a statistical power of 0.7. Patients were instructed to try to achieve smooth pedaling. Crank angular position and tangential forces were recorded; cadence, torque, power, cycling smoothness, and symmetry of the movement were deduced. The cadence was calculated from the change of crank position over time. This was digitally filtered with a second-order Butterworth filter with a cutoff frequency of 4 Hz. Torque was calculated by multiplying the sum of the left and right forces by the crank arm, and power was defined as the product of cadence and torque.

The method proposed by Chen et al. (2005) was used to measure the smoothness of reciprocal pedaling. In their approach, the instantaneous cycling cadence is an undulating curve along the pedaling cycle, rather than a straight line as would be expected in ideally smooth pedaling. The cadence was approximated with a smooth curve in terms of a tenth-order polynomial fitting-curve (Fig. 1a).

The roughness index (RI), defined as the summation of the curvature for each instantaneous cranking speed, is given as

$$\mathrm{RI} = \sum_{1}^{360} \mathrm{d}R/\mathrm{d}s,$$

where R is the instantaneous cranking speed after polynomial curve fitting, and s is the crank position. In smooth pedaling, the RI will approach zero. To measure cycling symmetry, a slightly modified definition of the symmetry index (SI), as proposed by Chen et al. (2005), was used. To obtain a similar measure of the muscle activity of both legs, the maximum of the circular auto-correlation coefficient of the crank torque profile (Fig. 1b) was calculated as follows:

$$SI = \max_j \mid c_{xx}(j),$$

where j is the angular lag between the two highest peaks of the crank torque profile taken over one pedaling cycle of 360°. The higher the SI is as it approaches the maximum value of 1, the higher the side symmetry is in torque generation during cycling movement. Chen and colleagues measured torque indirectly by using electromyography (Chen et al., 2005). Polynomial regression and interpolation of the cadence and the torque to 1° crank angle of the pedaling cycle for the eight 15-s periods for each subject and condition yielded eight cadence and torque profiles which resulted in eight observations of the parameters power, RI, and SI.

2.6. Statistical analysis

Correlation and regression analyses were performed to determine the relationships between electrically evoked torques on the affected side and volitionally generated torques

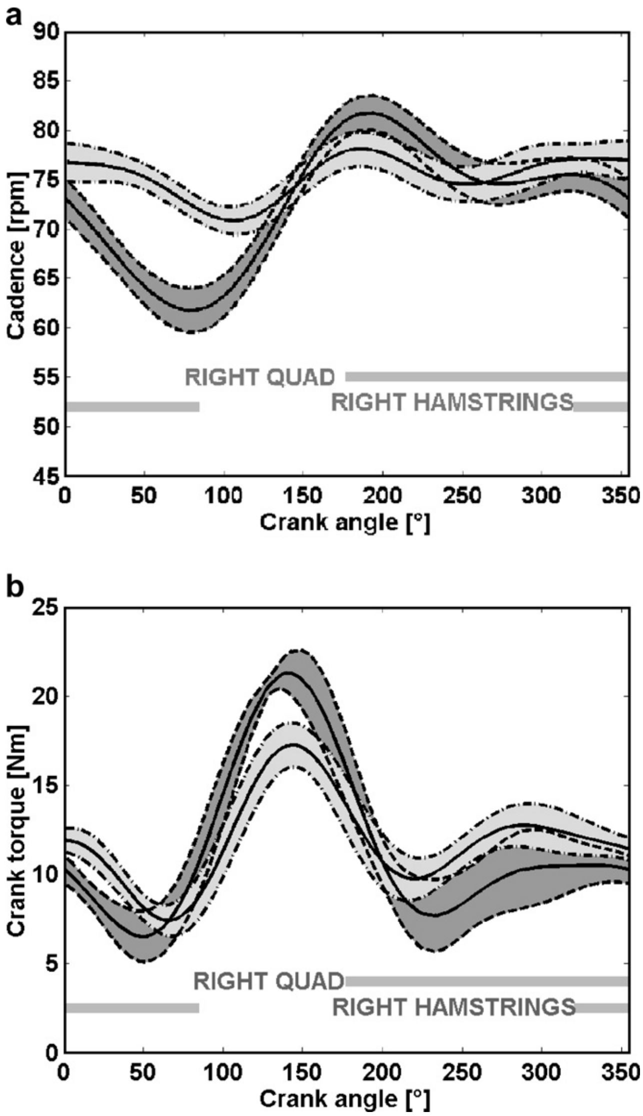

Fig. 1. Cadence (a) and crank torque (b) profiles measured in stroke subject #1 during only volitional (dark gray) and FES-supported (light gray) cycling conditions. Continuous curves and shaded area limited by dashed and dashed-dotted lines represent the average plus or minus one standard deviation based on data taken over eight 15-s intervals. Zero degrees refer to the left, backward-pointing crank arm. The stimulation intervals of quadriceps (QUAD) and hamstrings muscles are represented by horizontal gray bars. The right quadriceps stimulation range corresponds approximately to the right push phase. Subject # 1 had a right-sided hemiplegia (Fig. 1b), which caused asymmetrical torque production during purely volitional cycling (symmetry index, SI): mean 0.11 (SD 0.03)). Supportive FES on the right side led to a significantly ($P = 0.04$) larger SI: mean 0.20 (SD 0.09) for this subject. Smoothness (Fig. 1a) significantly improved ($P = 0.04$) as the mean roughness index (RI) decreased from 43 (SD 4) without FES to 23 (SD 4) with FES.

on the affected and non-affected side, as well as the relationship between the electrically evoked torques and the maximal tolerated stimulation intensity. Then the averages and standard deviations were computed for the eight observations of the power, RI, and SI parameters for each individual and condition. Interconditional comparisons were made for each subject.

Finally, to investigate the effect of the electrically generated torque on the kinematics and kinetics of cycling, the mean data for all study participants were pooled. Correlation and regression analysis were used to examine the hypothesized dependency of the FES-supported changes of power, smoothness (RI), and symmetry (SI) from the maximum of electrically evoked torque.

As normal distribution could not be assumed, the non-parametric paired Wilcoxon test, Spearman's rank correlation test, and regression analysis were used. All analyses were performed with the Statistics Toolbox in Matlab V. 6.1.0. (The MathWorks Inc, Natick, USA).

3. Results

3.1. Isometric measurements

Fig. 2 shows the side distribution of volitionally (affected vs. non-affected side) and electrically evoked crank torques on the affected side of the study participants. It represents graphically the amount of symmetry between the torques produced by the legs. A healthy subject with a side-symmetrical pattern of torques would be plotted near the $y = x$ straight line in the graph. It is usually impossible for even a healthy subject to have total symmetry of muscle activity due to the dominance of one side and small variations in leg usage during pedaling. The asymmetry between the affected and non-affected legs in hemiparetic subjects was mean 39% (SD 25, range 0–88%), because of the large variability of the voluntary torque generated by the affected (mean 21 N m (SD 16)) and the non-affected legs (mean 57 N m (SD 27)). The electrically evoked torque amounted to mean 4.0 N m (SD 4.1, range 0–13.6 N m); it was achieved at the maximal tolerated stimulation intensities of mean 60.8 mA (SD 30.0).

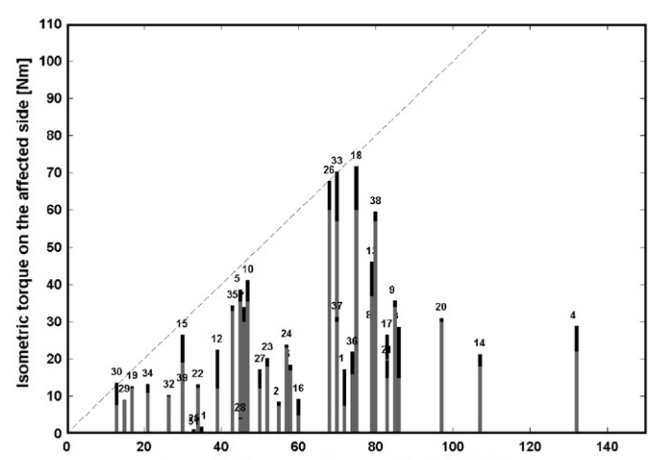

Fig. 2. Mean isometric crank torques generated volitionally (gray bars with abscissa: non-affected side and height of the bar: affected side) and evoked electrically on the affected side (height of black bars). The bars are indexed by the ID number of the subject. Individuals with perfect side symmetry of torques would be represented by the $y = x$ (dashed) line.

Significant correlations were found between the electrically evoked and the maximum of volitional torque generated by the affected as well as the non-affected legs ($P = 0.01$ and $P = 0.02$, respectively). These correlations were moderate (Spearman's correlation coefficient (rs) = 0.37 and 0.44, respectively). Therefore the variance of the volitional torques could not explain the variance of the electrically evoked torques (that of the affected and the non-affected legs amounted to only 16% and 13%, respectively). A larger correlation was found between the maximum of electrically evoked torque and the maximal tolerated stimulation intensity (rs = 0.63, $P < 0.001$). Accordingly, the electrically evoked torque was better explained by the maximal tolerated stimulation intensity (58%) than by the volitional torques.

3.2. Ergometric measurements

3.2.1. Power

The mean of the pooled data for power for all periods and all participants amounted to 51 W (SD 21) and 53 W (SD 26), respectively, during purely volitional and combined (volitional supported by electrical stimulation) cycling. The individually measured power significantly increased in only three subjects when FES was added (## 18, 33, and 36).

3.2.3. Smoothness

Pooling the smoothness (RI) data of all participants showed that the mean roughness of crank speed in only the volitional contraction decreased from 43.8 (SD 20.4) to 37.6 (SD 16.8) during stimulation-supported volitional contraction. The mean pooled improvement of smoothness (ΔRI) amounted to 6.2 (SD 11.7). Individual analysis (Fig. 3) showed that 10 of 39 subjects (26%) significantly ($P \leqslant 0.05$) improved the smoothness of their cycling movement using FES (mean 83 mA intensity, SD (27)), while the remaining 29 subjects did not show any significant changes of RI (mean 52 mA intensity, SD 26). Significant improvements generally occurred in subjects who had larger electrically evoked torques; 8 of these 10 subjects (80%) generated torques exceeding 5.5 N m. These patients are graphically represented in the right upper and middle parts of (Fig. 3). No significant improvements of RI were found in 29 subjects. The majority of these subjects could generate only small torques with FES. Twenty-four subjects, i.e., 83% of all participants, showed no significant improvements of RI; they could only evoke less than 5.5 N m additional torque using FES in the isometric measurement. These subjects clustered in the left lower corner of the graph (Fig. 3).

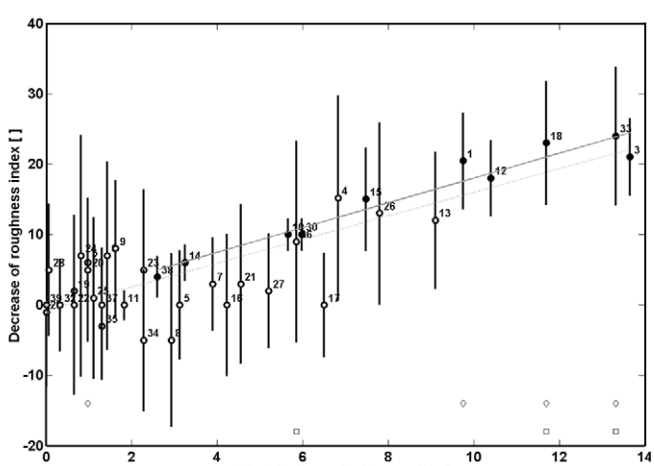

Fig. 3. Dependence of mean improvement of smoothness ΔRI on mean electrically evoked torque ΔT. Circles representing the subjects are indexed by the corresponding ID number. Closed and open circles denote significant and non-significant, respectively, changes of ΔRI. Standard deviations of ΔRI are represented as thin vertical segments. Two kinds of regressions were computed: for all 39 study participants (gray dotted line) and for only participants with significant increase of smoothness (gray continuous line). Four and three subjects also significantly increased their symmetry (SI) and power, respectively (mean values represented by diamonds and squares).

3.2.4. Symmetry

The mean side-related symmetry of the torques amounted to 0.13 (SD 0.11) and 0.18 (SD 0.14) in the case of volitionally and electrically supported cycling, respectively. The mean increment of symmetry ΔSI was correspondingly 0.04 (SD 0.15) using FES. Only 4 of 39 participants significantly ($P \leqslant 0.05$) increased their cycling symmetry SI (## 1, 2, 18, and 33), the remaining 35 did not. For this reason the dependencies of power (ΔP) and symmetry increments (ΔSI) on electrically evoked torque were not assessed by correlation analysis.

3.2.5. Dependence of improvement of smoothness (ΔRI) on electrically evokable torque ΔT

The analysis of the pooled smoothness data of all subjects (in each case as an average over 8 observations) revealed significant correlations between the improvement of smoothness (ΔRI) of the cycling movement and the electrically evokable isometric torque (ΔT): the Spearmann correlation coefficient was 0.66 with $P = 0.001$ and statistical power = 0.998. The corresponding linear regression showed that 70% of the ΔRI variance could be explained well by ΔT variance. Fig. 3 suggests that subjects represented in the ΔRI against ΔT plot can be divided into two different groups: those with significant improvement of RI (10 subjects) and those without (29 subjects). If only the 10 subjects with significant improvement of RI are used in the correlation and regression calculations, then the Spearman correlation coefficient increased to 0.94 (with $P = 0.001$ and statistical power = 0.995). The explainable variance thus amounted to 94%. In contrast, if only subjects with no significant improvement in ΔRI were considered, the linear relationship between ΔRI and ΔT was not significant ($P > 0.1$).

4. Discussion

Cycling may be successfully used in patients with SCI, when the primary goal is to increase power and endurance.

It was recently shown, however, that it is equally important for these patients to achieve smooth pedaling, because smoothness of pedaling improves the functional outcome (power and endurance) of FES cycling (Szecsi et al., 2007b).

Before our study it was unclear which quantitative parameters, kinetic or kinematic, were influenced by FES cycling in hemiplegics (Ferrante et al., 2006; Chen et al., 2006). We have shown that the smoothness of cycling movements (defined as roughness index of cadence speed) is the most sensitive and suitable parameter that could be influenced in patients with hemiplegia.

RI significantly decreased in 10 of the 39 patients with subacute hemiplegia (26%) during electrical stimulation. Power and symmetry (SI) were improved in only a small fraction of patients (3 and 4 of 39, corresponding to 8% and 10%, respectively). Therefore, our data do not confirm the more optimistic predictions in the literature (Chen et al., 2006; Ferrante et al., 2006) about the biomechanical efficacy of FES cycling in hemiplegic subjects.

This discrepancy might be due to the fact that earlier cycling studies relied partly on a few patients with hemiplegia (Chen et al., 2006, 2005; Ferrante et al., 2006) and partly on patients with chronic hemiparesis. The largest published study (Chen et al., 2005) investigated volitional cycling of 13 patients in whom the mean time since stroke was 25 months (SD 19). Our study included only patients with subacute stroke (mean time since stroke 10.9 weeks (SD 5.9)). They are an important target group for the proposed therapy.

The quantitative kinematic analysis showed that the hemiparetic subjects in our study exhibited less smoothness (higher mean RI 43.8 (SD 20.4)) during volitional contractions at a mean workload of 51 W (SD 21), as opposed to that reported in the literature, where RI ranged from 32 to 43 at workloads of 90–180 W (Chen et al., 2005). Because of the weakness of the paretic leg in the early phase of convalescence after stroke, patients with subacute stroke were able to cycle only at lower loads than patients with chronic stroke in the later phase. Moreover, at the cycling workloads used in our study, the non-affected leg of the subject with hemiparesis provided adequate muscle force without FES to complete the cycling movement and also to compensate for the weak leg. Supportive pedaling with FES on the affected side did not significantly increase the contribution of the affected leg to crank turning (symmetry) in most cases (35). In a minority of cases (4) the contribution of the affected leg complemented the generally reduced contribution of the non-affected leg (Fig. 1b). Therefore, power as a rule does not significantly increase when FES is applied on the affected side (only in 3 of 39 patients).

Our kinetic analysis of cycling showed less symmetry in volitional cycling (mean SI 0.13 (SD 0.11)) than observed by others (Chen et al., 2005). Moreover, most of our patients did not achieve significant improvement of SI with additional stimulation of the affected leg (only 4 of 39). This can, in our opinion, be at least partly explained by the different definitions of SI. While the originally proposed definition of SI (Chen et al., 2005, 2006) was based on linear envelope EMG, we used dynamic torque-related SI in this study as a direct measure of activity symmetry. The EMG-based SI requires sophisticated EMG devices with stimulation-pulse blinding which makes it difficult to use for the clinical evaluation of FES cycling of hemiplegics.

The question arose as to whether parameters like power or symmetry could be eventually improved with additional exposure, at least for more than one session. Yan and colleagues showed that 30 min of daily FES stimulation of the leg musculature in patients with subacute hemiplegie, 5 times weekly, for 3 weeks resulted in significant improvement of the isometric force, which is attributable to FES stimulation (Yan et al., 2005). Therefore, one can expect additional improvement in smoothness and also in power and symmetry with long-term exposure to FES cycling.

The second goal of this study was to ascertain why some hemiplegic subjects (10 of 39 in the present study) can improve their smoothness of cycling in the early phase after stroke, while others (29) cannot. The answer to this question allows selection of those individuals who would benefit from FES-cycling therapy, and it indicates the importance of the proposed method for the given population of subjects with hemiplegia.

Fig. 3 suggests that two different mechanisms have to be considered to understand the influence of FES on the kinematics of hemiplegic cycling. The 29 subjects without any significant improvement of smoothness generally evoked low torques with FES and also tolerated low stimulation intensities. In these patients we only observed statistically insignificant and unstable improvements of the kinematics (smoothness), perhaps due to occasional and unstable mobilizing of supplementary volitional forces triggered by pain. In the other 10 subjects the significant improvements of the kinematics had predominantly mechanical causes; the increase of smoothness (decrease of RI) depends strongly and linearly on the ability of the FES-stimulated paretic muscle to evoke torques. This ability in turn depends essentially on the individual's sensibility to pain caused by the surface current stimulation. To a lesser extent, it also depends on the volitional torque generated by the affected or non-affected legs. Since the amount of stimulation is limited by the subject's pain tolerance, it is interesting to speculate on how much of the muscle could theoretically be stimulated electrically and how close the torque evoked by the maximal tolerated stimulation intensity is to the maximal torque obtainable. Persons with subacute stroke were recently shown to have a voluntary activation of about 50% in the paretic leg musculature (Horstman et al., 2008); the maximal voluntary torque of the affected side amounts to about 42 N m on average in our study. Therefore only about 10% (4 N m) could be recruited electrically on average, by using 20-Hz burst stimulation at average intensities of 61 mA. There are to the best of our knowledge no alternative stimulation protocols available that can be used in FES cycling to generate more torque with less pain (Szecsi et al., 2007a).

5. Conclusion

The main effect of FES-assisted cycling in subjects with subacute hemiparesis is more an improvement of smoothness of pedaling than an increase in muscle power. Thus, the functional relevance of FES cycling for patients with subacute acute stroke probably consists mainly in strengthening the affected (weak) leg, reestablishing the side balance of forces, and improving pedaling control. From the viewpoint of biomechanical efficacy, FES-supported cycling is a feasible therapeutic alternative for only a quarter of subjects with subacute hemiparesis.

Further studies have to be performed to determine whether long-term repetitive application of biomechanically effective stimulation is therapeutically more advantageous than plain, sensory stimulation.

Conflict of interest statement

All financial and personal relationships with other people and organizations that could inappropriately influence (bias) the work have been disclosed.

Acknowledgements

This study was supported by the Else Kröner-Fresenius Foundation. The authors would like to thank Judy Benson for copyediting the manuscript.

Appendix A

Stimulation intervals used in all patients. Only one side was stimulated in a particular patient. Zero degrees refers to the backward-pointing left crank arm.

Muscle group	Start (°)	Stop (°)
Left quadriceps	18	187
Left hamstrings	87	254
Right quadriceps	182	12
Right hamstrings	256	62

References

Bobath, B., 1994. Adult Hemiplegia: Evaluation and Treatment. Butterworth-Heinemann Ltd., Oxford.

Brown, D.A., Kautz, S.A., 1998. Increased workload enhances force output during pedaling exercise in persons with poststroke hemiplegia. Stroke 29, 598–606.

Brown, D.A., Kautz, S.A., 1999. Speed-dependent reductions of force output in people with postroke hemiparesis. Phys. Ther. 79, 919–930.

Brown, D.A., Kautz, S.A., Dairaghi, C.A., 1997. Muscle activity adapts to anti-gravity posture during pedalling in persons with post-stroke hemiplegia. Brain 120 (Pt 5), 825–837.

Burridge, J.H., Taylor, P.N., Hagan, S.A., Wood, D.E., Swain, I.D., 1997. The effects of common peroneal stimulation on the effort and speed of walking: a randomized controlled trial with chronic hemiplegic patients. Clin. Rehabil. 11, 201–210.

Chen, H.Y., Chen, S.C., Chen, J.J., Fu, L.L., Wang, Y.L., 2005. Kinesiological and kinematical analysis for stroke subjects with asymmetrical cycling movement patterns. J. Electromyogr. Kinesiol. 15, 587–595.

Chen, J.J., Chen, H.Y., Chen, S.C., Chen, C.C., 2006. Clinical applications of FES-cycling to SCI and stroke subjects for smoother and symmetrical movement patterns. In: 11th Annual Conference of the Functional Electrical Stimulation Society. Miyagi-Zao, Japan.

Dietz, V., Ketelsen, U.P., Berger, W., Quintern, J., 1986. Motor unit involvement in spastic paresis. Relationship between leg muscle activation and histochemistry. J. Neurol. Sci. 75, 89–103.

Ferrante, S., Pedrocchi, A., Ferrigno, G., Molteni, F., 2006. FES-cycling treatment on hemiplegic patients: preliminary results. In: 11th Annual Conference of the Functional Electrical Stimulation Society. Miyagi-Zao, Japan.

Giuliani, C.A., Harro, C.C., Rosecrance, J.C., 1989. The effects of bicycle pedalling on the temporal-distance and EMG characteristics of walking in hemiplegic subjects. Phys. Ther. 69, 367–371.

Glaser, R.M., 1994. Functional neuromuscular stimulation. Exercise conditioning of spinal cord injured patients. Int. J. Sports Med. 15, 142–148.

Glenn, W.W., Phelps, M.L., 1985. Diaphragm pacing by electrical stimulation of the phrenic nerve. Neurosurgery 17, 974–984.

Glinsky, J., Harvey, L., Van es, P., 2007. Efficacy of electrical stimulation to increase muscle strength in people with neurological conditions: a systematic review. Physiother. Res. Int. 12, 175–194.

Hachisuka, K., Umezu, Y., Ogata, H., 1997. Disuse muscle atrophy of lower limbs in hemiplegic patients. Arch. Phys. Med. Rehabil. 78, 13–18.

Horstman, A.M., Beltman, M.J., Gerrits, K.H., Koppe, P., Janssen, T.W., Elich, P., De Haan, A., 2008. Intrinsic muscle strength and voluntary activation of both lower limbs and functional performance after stroke. Clin. Physiol. Funct. Imaging.

Hunt, K.J., Stone, B., Negard, N.O., Schauer, T., Fraser, M.H., Cathcart, A.J., Ferrario, C., Ward, S.A., Grant, S., 2004. Control strategies for integration of electric motor assist and functional electrical stimulation in paraplegic cycling: utility for exercise testing and mobile cycling. IEEE Trans. Neural Syst. Rehabil. Eng. 12, 89–101.

Hwang, I.S., Lee, H.M., Cherng, R.J., Chen, J.J., 2003. Electromyographic analysis of locomotion for healthy and hemiparetic subjects–study of performance variability and rail effect on treadmill. Gait Posture 18, 1–12.

Kralj, A., Acimovic, R., Stanic, U., 1993. Enhancement of hemiplegic patient rehabilitation by means of functional electrical stimulation. Prosthet. Orthot. Int. 17, 107–114.

Malezic, M., Hesse, S., 1995. Restoration of gait by functional electrical stimulation in paraplegic patients: a modified programme of treatment. Paraplegia 33, 126–131.

Malezic, M., Kljajic, M., Acimovic-Janezic, R., Gros, N., Krajnik, J., Stanic, U., 1987. Therapeutic effects of multisite electric stimulation of gait in motor-disabled patients. Arch. Phys. Med. Rehabil. 68, 553–560.

Malezic, M., Hesse, S., Schewe, H., Mauritz, K.H., 1994. Restoration of standing, weight-shift and gait by multichannel electrical stimulation in hemiparetic patients. Int. J. Rehabil. Res. 17, 169–179.

McComas, A.J., Sica, R.E., Upton, A.R., Aguilera, N., 1973. Functional changes in motoneurones of hemiparetic patients. J. Neurol. Neurosurg. Psychiatry 36, 183–193.

Mohr, T., Podenphant, J., Biering-Sorensen, F., Galbo, H., Thamsborg, G., Kjaer, M., 1997. Increased bone mineral density after prolonged electrically induced cycle training of paralyzed limbs in spinal cord injured man. Calcif. Tissue Int. 61, 22–25.

Pape, K.E., Kirsch, S.E., Bugaresti, J.M., 1990. New therapies in spastic cerebral palsy. Contemp. pediatr., 13.

Perkins, T.A., De, N., Fitzwater, R., Phillips, G.F., Wood, D.E., 2001. Leg powered paraplegic cycling system using surface functional electrical stimulation. In: IFESS. Proceedings of the 7th Vienna International Workshop on Functional Electrical Stimulation. Vienna, Austria.

Perkins, T.A., De, N.D.N., Hatcher, N.A., Swain, I.D., Wood, D.E., 2002. Control of leg-powered paraplegic cycling using stimulation of the lumbo-sacral anterior spinal nerve roots. IEEE Trans. Neural Syst. Rehabil. Eng. 10, 158–164.

Potempa, K., Lopez, M., Braun, L.T., Szidon, J.P., Fogg, L., Tincknell, T., 1995. Physiological outcomes of aerobic exercise training in hemiparetic stroke patients. Stroke 26, 101–105.

Rosecrance, J.C., Giuliani, C.A., 1991. Kinematic analysis of lower-limb movement during ergometer pedaling in hemiplegic and nonhemiplegic subjects. Phys. Ther. 71, 334–343.

Szecsi, J., Fornusek, C., Krause, P., Straube, A., 2007a. Low-frequency rectangular pulse is superior to middle frequency alternating current stimulation in cycling of people with spinal cord injury. Arch. Phys. Med. Rehabil. 88, 338–345.

Szecsi, J., Krause, P., Krafczyk, S., Brandt, T., Straube, A., 2007b. Functional output improvement in FES cycling by means of forced smooth pedaling. Med. Sci. Sports Exerc. 39, 764–780.

Yan, T., Hui-Chan, C.W., Li, L.S., 2005. Functional electrical stimulation improves motor recovery of the lower extremity and walking ability of subjects with first acute stroke: a randomized placebo-controlled trial. Stroke 36, 80–85.

Zorowitz, R.D., 2006. Neurorehabilitation of the stroke survivor. In: Selzer, M.E., Clark, S., Cohen, L.G., Duncan, P.W., Gage, F.H. (Eds.), Textbook of Neural Repair and Rehabilitation. Cambridge University press, Cambridge.