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Assisted leg displacements and progressive loading by a tilt table combined with FES promote gait recovery in acute stroke

Solopova IA[1,3], Tihonova D.Y.[2], Grishin AA[1,3], Ivanenko YP[4]

[1]Institute for Information Transmission Problems of RAS, Moscow, Russia; [2]Russian Medical State University, Moscow, Russia; [3]Central Clinical Hospital of RAS, Moscow, Russia; [4]IRCCS Foundazione Santa Lucia, Rome, Italy

Corresponding author:
Dr. Irina Solopova
Laboratory of Neurobiology of Motor Control
Institute for Information Transmission Problems, Russian Academy of Science,
Bolshoy Karetny 19, Moscow 127994, Russia
Ph(+7)495-6502895
Fax(+7)495-6500579
e-mail: solopova@iitp.ru

Abstract

Objective: Here we developed and tested a novel system for early motor rehabilitation in acute stroke when patients are unable to stand and walk without assistance. Stepping performance may be largely facilitated by providing treatment in the supine position on a tilt table using step-synchronized functional electrical stimulation (FES) with assisted leg movements and progressive limb loading. **Methods:** Sixty-one individuals with acute stroke were randomly assigned to two groups, experimental and control. The first group received both a conventional therapy and FES-therapy combined with progressive limb loading, whereas the control group received a conventional therapy only. Changes after treatment were assessed using clinical scores and neurophysiological measurements of movement performance. **Results:** After treatment, there was an improvement of the clinical scores, muscle forces and everyday life activity performance in both groups, however, significantly higher in the experimental group. Active rhythmic movements of the non paretic leg often provoked muscle activity in the paretic leg as well as there was a reduction of the contralateral leg muscle contraction during paretic leg movements. **Conclusion:** The developed FES and leg displacement-assisted therapy facilitates a smooth transition to walking in the vertical position and increases the patient’s functional abilities and the effectiveness of rehabilitation.

Key words: neuromotor rehabilitation, locomotor movements, EMG patterns, functional electrical stimulation, acute period of stroke

Introduction

The problem of motor neurorehabilitation after stroke, as a major cause of disability, is significant and complex. Numerous studies have shown that motor activity after brain damage plays a critical role in neurophysiological reorganization, which may occur in the areas adjacent to the damage [1,2]. The lack of adequate rehabilitation may lead to the appearance of irreversible anatomical and functional changes, as well as progressive weakness in the affected leg. More than a half the patients are unable to walk in the acute period, and gait impairments are still present 3 months after the stroke [3]. Many patients develop an abnormal stereotype of movement during walking, which is difficult to correct [4,5,6].

It may be reasonable to perform a course of training aimed at improving muscle strength and appropriate locomotor pattern, prior to the onset of unaided walking or posture maintenance. Thus, various systems of supported walking are often used [7,8,9]. However, in the acute stroke period the patient's ability to be in an upright position is limited. Therefore, the rationale of this study was to model and reinforce stepping movements initially in the supine position, with gradual patient verticalization, and in combination with step-synchronized functional electrical stimulation (FES). FES has been shown to be an effective tool for muscle strength augmentation and improvements in walking in neurological patients [10,11]. Furthermore, FES application in stroke patients may allow a better functional outcome in a shorter time [12,13,14]. The effectiveness of FES combined with body weight support has also been demonstrated in hemiplegic patients [15]. This study intended to provide support for the importance of early motor rehabilitation in stroke patients, and to introduce a novel motor neurorehabilitation system combining three aspects of treatment: 1) gradual verticalization of the patient in the supine position, 2) passive or active locomotor-like movements, and 3) step-synchronized FES of leg muscles.

Methods

Subjects

Sixty one subjects with first acute stroke and 10 neurologically normal subjects participated in the study. They were selected if they had stable hemodynamics in the absence of significant lower limb contractures (with an Ashworth index < 2 in all the lower limb muscles: on average 0.9±0.6 [mean±SD]) or orthopedic impairment or significant cardiovascular impairments. Subjects were excluded from the study if they presented cardiac arrhythmia, trombophlebitis, significant perceptual, cognitive or communication impairments, diabetes, contra-indication for electrical stimulation (unstable epilepsy, cancer, skin abnormalities, pacemaker). The procedures were approved by the review body of the Central Clinical Hospital and conformed with the Declaration of Helsinki.

Design

Patients were pseudo-randomly assigned to one of two groups, experimental and control, based on clinical measurements to insure no significant differences between groups at baseline (Table 1). All patients received a conventional therapy (supervised physical therapy, including stretching, active or passive mobility and exercises). Patients in the experimental group received additionally FES-therapy combined with assisted leg movements and progressive limb loading (2 weeks of training, 30 min per day, 5 days per week).

Apparatus

The basic apparatus was a motorized tilt table with integrated robotic stepping technology specially designed for rehabilitation procedures in acute stroke patients that allowed both passive and active leg movements (Fig 1A) (Russian patent #2352316, 16.10.2007). It was equipped with an electrical motor for performing alternating passive leg movements and could be tilted by 30° to partially load the legs during the 'stance' phase. The feet were attached to footplates that could be moved back and forth along the low friction carriages either by the motor (passive mode) or by the subject (active mode). The maximal amplitude of carriage movements was 60 cm, and the maximal cadence of leg movements was 20 steps per minute. In the passive mode, the amplitude of foot motion was adjusted so that the amplitude and velocity (bell-shaped) profile of knee and hip flexion was similar to that of active stepping in place in healthy subjects in the same set-up. There was also a third mode of training (semi-active mode), in which the patients moved the non-paretic leg themselves while the affected (paretic) leg underwent alternating passive movements.

All three modes were used during training with progressive emphasis on the active mode and progressive tilting the couch depending on the ability of the patients to tolerate the loadings. Recordings were always made in the pre and post treatment (referred to as 'pre' and post') in the active mode (when the patient moved the legs) in the horizontal table position. The parameters for leg movements during FES therapy on the tilt table were selected individually for each subject. On average, the mean amplitude of carriage movements was about 20-30 cm; cadence - 8-9 steps/min at the beginning of treatment and 14 steps/min at the end of training. As a rule, early procedures were realized in the passive mode, but the patients were asked to 'participate' (help) in leg movements.

Functional Electrical Stimulation

Functional electrical stimulation (FES) was applied during leg movements on the tilt table. Pairs of electrodes were placed on the skin along the muscle with an electrode distance 20 cm on the following muscle groups of both legs: soleus, tibialis anterior (TA), hamstring, quadriceps, hip adductors, gluteus maximus and gluteus medius. We used electrodes of different size for stimulation: from 3x4 cm electrodes for smaller muscles (i.e. TA) to 3x8 cm for stimulation of lager muscles (i.e. quadriceps, hamstring). We used a specially designed suit (Fig. 1A) to facilitate quick electrode attachment to a patient's body [16]. A 16-channel stimulator (MNS 16-02, Russia) was used for stimulation (rectangular monophasic pulses; 65 Hz; maximum pulse amplitude 80 mA, pulse width 100 μs). Stimulation intensity was adjusted to each muscle individually before the procedure by smoothly increasing the current up to the level at which a visible weak or moderate muscle contraction was observed and the subject still felt comfortable. Using on-line feedback from foot (carriage) motion, each muscle group was stimulated according to a typical EMG profile observed in the healthy subjects during stepping movements [17] (Fig 1B,C): we stimulated hamstring and gastrocnemius-soleus muscles during knee flexion, and tibialis anterior, quadriceps femoris and gluteus maximus and medium, hip adductor during knee extension. During treatment, blood pressure and heart rate was monitored continuously.

Outcome measurements

The following clinical and biomechanical measurements were made before and after treatment. Motor function of lower limb was evaluated with the Fugl-Meyer scale [18]. Stroke severity was assessed by the National Institutes of Health Stroke Scale (NIHSS) [19] and European Stroke Scale (ESS) [20]. The Barthel Index (BI) [3] was used to determine the functional status of each patient. The hemiparesis severity was evaluated with a 6-graded scale [21]: paralysis (0) - no leg movements and no voluntary muscle contractions could be detected; severe paresis (1) – partial muscle contraction but without joint movements; pronounced paresis (2) – full range of joint movements under partial limb loading; moderate paresis (3) - full range of joint movements under full limb loading; light paresis (4) – movements under additional limb loading but weaker than on the non paretic side; normal muscle force production (5). We also monitored the ability of patients to perform everyday life activities before and after treatment: to sit, stand, move from wheelchair to bed, and walk along a short 10 m walkway with or without assistance.

Maximum isometric voluntary contraction (MVC) of knee flexors and extensors was performed in the supine position when the knee joint was fixed at 90° (hip angle ~ 45° and ankle angle ~ 80°). The subject was instructed to relax the contralateral extended leg as much as possible during MVC. The force was measured by the strain gauge and converted to the knee torque. Measurements in patients started with the non-paretic leg. The patient was given one attempt at the MVC (for training) before recordings. Overall, 12 trials were recorded with 6 trials on the non-paretic leg (3 for flexion, and 3 for extension) and 6 trials on the paretic leg, with a 1 min rest period between the trials. The mean force during a 3 s period before the command to perform MVC was used as a baseline. Strong verbal encouragement was given during each trial. The maximum force value obtained in each of the three attempts, was used for calculating MVC.

To assess patient's ability to perform "locomotor-like" movements on the table, the subjects were asked to perform alternating flexion-extension movements of both legs at a comfortable speed. Overall, three trials were recorded with a 1 minute rest period between trials. The duration of each trial was 60 s. Angular movements in the knee and ankle joints were recorded using potentiometers attached laterally to each joint of both legs.

The EMG activity of rectus femoris (RF), biceps femoris (BF), gastrocnemius medialis (GM) and TA muscles of both legs were recorded at 1kHz using surface bipolar electrodes (BAC Electronics Inc., Rockville, Md) with an inter-electrode distance of 2.5 cm. The skin was shaved and cleaned with alcohol prior to the electrode placement. EMG activity was pre-amplified and filtered (bandwidth 20Hz-1kHz). For assessment of EMG amplitudes, raw EMG signals were numerically rectified, low-pass-filtered with a zero-lag Butterworth filter at 10Hz cutoff.

Statistics

Descriptive statistics included means and standard deviation (SD) of the mean. The non-parametric Mann-Whitney U test was used to compare clinical scores and biomechanical values before and after treatment as well as their increments (Δ) after treatment between the experimental and control groups. The Wilcoxon test was performed to compare the same parameters before and after treatment within each group. The level of statistical significance was set at 0.05.

Results

Sixty one subjects (32M/29F; age: mean 64±18 (38 to 82 years) with first acute stroke (8.8±4.4 days post-stroke) participated in the study. There were no significant differences in the baseline clinical measurements (Table 1). Hemiparetic subjects had a sustained unilateral cerebrovascular accident in the basin of the middle cerebral artery according to computerized tomography. Fifty-three of them had an ischemic type of stroke, and 8 had a hemorrhagic type. All patients had a first right (19 subjects) or left (42 subjects) stroke, located in the motor cortex and involving some cortical and subcortical structures, such as internal capsule – 2 patients, frontal-parietal - 14 patients, thalamic lesion – 4 patients, temporo-frontal-parietal – 6 patients, temporal parietal – 10 patients, nucleus basalis – 13 patients, frontoparietotemporooccipitale – 4 patients, temporal parietal and nucleus basalis – 2 patients. Intracerebral hematoma was in 1 person, hematoma in the thalamus - in 2 patients, hematoma in the parietal region - in 2 patients, with cerebral infarction and haemorrhagic saturation - in 2 patients. Subjects experienced lower limb paresis to different degrees (Table 1).

MVC of knee flexors and extensors

No significant differences were found in the MVC of knee flexors and extensors of both paretic and non-paretic leg among subject groups (p=0.26 and p=0.94 for paretic leg and p=0.59 and p=0.46 for non-paretic leg, respectively). Fig. 2 (left panels) shows examples of EMG activity and joint torques in two patients before treatment. The paretic leg typically exerted weaker forces and lower EMG activity. After treatment, in the experimental group we found significant increment of the maximal extensor torque in both legs (p=0.01 and p=0.03 for paretic and non-paretic legs, respectively) and flexion torque in the paretic leg (p=0.002). In the control group, we also found significant increments in the muscle forces of the paretic limb (p=0.01), however, a comparison with the experimental group revealed significantly lower (~2 times) torque increments (post-pre, Fig. 3A right panels; p=0.03 and p=0.01 for extensors of the paretic and non-paretic legs, respectively, p=0.03 for flexors of the paretic leg). The non-paretic limb exerted similar forces after treatment in the control group.

Stepping movements

On average, performance of voluntary stepping movements (amplitude of movement in the knee and ankle joints, cadence) was similar in the two groups of patients prior to treatment. The non-paretic leg performed large-amplitude movements both before and after treatment: on average, knee joint oscillations were 81.5±14.2° and ankle joint movements 20.4±13.8°. Movements in the paretic leg were small if any prior to treatment (Fig. 2 right panels, Fig. 3B). After treatment, both groups of patients showed significant increments in the amplitude of knee joint motion. These increments tended to be larger in the experimental group (though not significantly, p=0.07). Ankle joint range of movements did not change significantly in the control group (p=0.43) while in the experimental group they increased by ~8° (66%) (p=0.0004) and increments were significantly larger than in the control group after treatment (p=0.03).

EMG activity during stepping-like movements

Fig. 4 illustrates changes in the mean EMG activity of proximal (driving) muscles during flexion and extension phases of knee movements. In healthy subjects, we typically observed activity in BF and MG muscles during knee flexion of the ipsilateral leg and in TA and RF during knee extention (Fig. 1B); there was also small EMG activity of BF in the contralateral (‘resting’) leg (Fig. 4B).

In both groups of patients, there was a substantial increment of EMG activity in the non-paretic leg (especially in the BF muscle) during movements of the paretic leg (even after treatment) with respect to healthy subjects, suggesting a sort of contralateral ‘help’ to the weak paretic limb (Fig. 2,4A,C). Furthermore, active rhythmic movements of the contralateral leg often provoked muscle activity in the paretic leg (Fig. 2 right panels). Interestingly, in three patients we observed BF activity in the paretic leg even though we failed to evoke BF contractions during maximal voluntary efforts (Fig. 2A).

After treatment, there was a significant improvement of EMG patterns during movements of the paretic leg in the experimental group with respect to the control group (Fig. 4C). In particular, RF and BF muscles increased their activity during knee flexion of the ipsilateral leg ($p=0.01$ and $p=0.04$, respectively), in part due to increments in the amplitude of knee and hip motion, while the control group displayed no changes. In the meantime, RF and BF activity of the contralateral leg significantly decreased in the experimental group while, in the control group, either there were no changes or RF activity even increased (Fig. 4C). The non-paretic limb displayed similar muscle activity both before and after treatment in both groups of subjects (Fig. 4D).

Clinical scores

All patients in the experimental group positively assessed treatment on the tilt table. After therapy (on average, on the 20nd day after stroke), both groups of patients showed improvement in their general status, overall motor activity and clinical scores. The reduction in the degree of hemiparesis [21] is illustrated in Fig. 3C. After treatment, 20 patients (63%) of the experimental group had only light hemiparesis, while only 3 patients (10%) in the control group.

This was reflected also in the overall dynamics of changes in the clinical scores (Table 1), the improvement was significantly higher in the experimental group ($p<0.05$). Since the Fugl-Meyer scale is one of the most used scales for assessment of motor function of the leg, we performed an additional analysis of this index depending on the initial degree of paresis (Table 2). The results revealed non-uniform recovery of the motor function of the paretic limb. The most prominent recovery was observed in the experimental group with paralysis or severe paresis rather than with pronounced paresis ($p=0.001$ and $p=0.02$, respectively), whereas recovery in the control group did not depend significantly on the initial degree of hemiparesis ($p=0.25$). For all three levels of severity, there was greater recovery of motor function as shown by the FMS in the experimental group ($p<0.05$).

The analysis of improvement of clinical scores in patients with left or right stroke did not reveal significant differences. However, localization of the pathological focus affected the degree of impairment and the dynamics of recovery. Patients with stroke localization in the internal capsule revealed most severe impairments in the motor function and worse recovery.

Significant improvements were observed also in performance of everyday life activities (Table 3). If prior to treatment, patients with light and moderate paresis needed the help of 2 persons to move from the wheelchair to the bed, following treatment they could move themselves. As well, beginning at 6-7 days after the onset of treatment they could maintain an upright posture and walk overground with the help of one therapist. Patients with pronounced paresis required the need of one person to displace from wheelchair to bed and 2 persons to stand and walk. In the control group, these abilities were lower (Table 3) and patients either sat or just tried to stand near their bed with arm support. Thus, a greater number of patients in the experimental group (relative to the control group) were able to accomplish specific activities of daily living following treatment.

Discussion

Rehabilitation with the help of the new apparatus strongly influenced the motor recovery of patients. Also, active rhythmic movements of the contralateral leg often provoked muscle activity in the paretic leg. These results suggest that stepping with knee and hip extension and flexion provides proprioceptive or supraspinal inputs to the spinal cord that increases motor recruitment compared to voluntary efforts [22] and may perhaps account for a better improvement of MVC and clinical scores in the experimental group. This new system with the possibility of progressive inclination towards verticalization prepared patients for a smooth transition to the upright position, gradually increasing the load on the legs. As a consequence, more patients in the experimental group began to walk independently by the end of treatment. Despite all the advantages of training in the new apparatus in conjunction with the use of FES, it is worth emphasizing that this rehabilitation program does not replace the daily applicable standard therapeutic treatment and serves only as an addition to them. An important aspect of treatment, in our view, is that the treatment on the motorized stepping table is accompanied by the active participation of the patient and decreases the burden on nurses.

Functional stimulation in recent years is increasingly used in the rehabilitation of patients with neurological diseases [14]. Increased strength of shank and thigh muscles, more substantial than in the control group, was shown in patients who were treated with FES, applied both in the acute phase of stroke (the beginning of treatment at 8.7±5.8 day) [12] and in a later period (beginning of treatment at 56±22 day) [13]. In our study the experimental group demonstrated a significantly greater increase in muscle strength compared with the control group: ~2 times for the extensors and flexors of the paretic limb (Fig. 3A). It should also be noted that there was a significant increase in strength for the extensor muscles of the non paretic limb, which was not significant in the control group (Fig. 3A, right panel). Furthermore, after treatment in the experimental group, the ankle became more actively involved in the movement (Fig. 3A). As well, the contralateral involvement or co-contraction decreased following therapy (Fig. 4C), which suggests a decrement of bilateral influences as discussed by Kautz and colleagues [23,24]. Thus, our results confirmed the effect of FES to strengthen muscles and increase the range of motion in joints of patients after stroke. The FES was delivered in reference to the timing of natural muscle excitation during movement (Fig. 1). As a result, the locomotor centers or networks are excited or released from inhibition in phase with their expected activity and thus may be accessible for correction or stimulating effects [10]. In addition, it is assumed that in the early stages of motor learning an increase in synaptic transmission in the existing neural circuits or the formation of new synapses occur [25]. Repetitive motion of paretic lower limb in patients after a stroke accompanied by functional electrical stimulation might contribute to the motor cortical reorganization. Such neuroplasticity and rapid motor learning could be the basis of better progress in the group receiving additional therapy.

We cannot rule out a significant contribution of repetitive movements per se that seem to be effective in rehabilitation and motor learning [7,26,27]. For instance, cycling training that requires compensatory action (when exposed to variability in cycling resistance [27]) or exploits intrinsic variability during assist-as-needed step training [28], produces greater improvement in motor performance. Therefore, the inclusion of FES may provide additional sensory reinforcement which ultimately improves learning. As well, previous research suggests that the integration of electrical therapy into exercise-active movement mediated by electrical activation of peripheral and central sensory-motor mechanisms enhances motor re-learning following damage to the central nervous system [14].

The factors determining the effectiveness of rehabilitation are the size and location of the lesion in relation to functionally important areas. The most severe motor defect and the worst recovery of movements were observed with localization of the lesion in the posterior internal capsule. With impairment of the internal capsule, basal ganglia, and thalamus, contractures of the paralyzed limb often occur that hinder rehabilitation of movements. Our study showed that patients with the localization of stroke in the basal ganglia and internal capsule recovered more slowly. Also, according to the literature there is some dependence of motor function recovery on the affected hemisphere. For instance, in patients with ischemic focus in the right hemisphere recovery is less active and there are more serious impairments of motor functions and autonomic processes [29]. In our study, the dynamics of recovery in patients did not depend on the lateralization of stroke.

According to the international recommendations [30], rehabilitation should start immediately after clinical stability has been achieved, because the most significant motor recovery occurs in the first few weeks after brain damage. For moderate or small strokes and small limited hematomas (without breaking the blood into the ventricles), treatment can be started on the 5th day after stroke. Early rehabilitation can also avoid a number of complications during the acute stroke period, largely due to hypokinesia and physical inactivity (thrombophlebitis of extremities, trombrembolii of pulmonary artery, pulmonary congestion, pressure sores, etc.). Early rehabilitation can also decrease the risk of development and progression of secondary pathological conditions (increased spasticity, contracture formation, joint pain in the paretic limb, developing incorrect motor strategy by patient). In our study, treatment started on the 8.8±4.4 day after stroke. Since there were no significant differences in the baseline values among subject groups, the difference in the recovery rate was mainly associated with leg movement training on the tilt table.

Summary

The results showed that FES-assisted therapy of rhythmic leg movements on the tilt table during acute stroke period is an effective rehabilitation tool, contributing to the reduction of clinical symptoms, muscle force improvement and everyday life activity performance enhancement. It facilitates a smooth transition to walking in the vertical position and thus increases the patient's functional abilities and the effectiveness of rehabilitation.

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Table 1. Subject characteristics for each treatment group.

	Experimental group (n=32)		***Control group (n=29)***	
days after stroke	8.2±4.3		9.3±4.5	
sex (M/F)	15/17		18/11	
ishemic/hemorragic (I/H)	27/5		26/3	
plegic side (R/L)	10/22		9/20	
	pre	post	pre	post
BI score	17.1±2.2	76.9±6.6*#	16.9±1.9	42.35±6.2*
NIHSS score	9.8±2.8	4.2±2.5*#	9.2±2.9	6.4±2.0*
ESS score	46.5±1.8	80.2±3.8*#	48.5±4.7	65.4±4.3*
FMS score	11.4±1.5	28.3±2.4*#	9.2±1.1	16.7±1.7*

BI –Barthel Index; NIHSS - National Institutes of Health Stroke Scale; ESS - European Stroke Scale; FMS - Fugl-Meyer Scale.
*p<0.05 significant differences between pre and post sessions within a group;
# p<0.05 significant differences between the 2 groups.

Table 2. The changes in the motor function of the paretic limb by the Fugl-Meyer scale after treatment.

Hemiparesis severity	***Experimental group***		***Control group***	
	pre	post	pre	post
paralysis	4.1±2.0	21.7± 6.7*#	5.5±0.8	11.6±1.7*
Severe hemiparesis	10.6±3.1	28.5±3.8*#	8.7±2.9	16.4±3.9*
Pronounced hemiparesis	17.3±3.2	31.1±2.1*#	13.7±0.7	17.6±2.7*

*p<0.05 significant differences between pre and post sessions within a group;
# p<0.05 significant differences between the 2 groups.

Table 3. Ability (number of subjects) to perform specific activities of daily living before and after treatment.

activity	***Experimental group (n=32)***		***Control group (n=29)***	
	pre	post	pre	post
assistance needed for the displacement from the wheelchair to the bed	32	5	29	16
self-maintained sitting posture	10	28	8	22
unaided standing	—	28	—	17
unassisted walking in the ward	—	28	—	17

Legends to figures

Fig. 1. Experimental set-up and FES procedure. A – tilting couch with integrated robotic stepping technology. B – an example of EMG and kinematic patterns during rhythmic voluntary leg movements in one representative healthy subject. C – FES timing. The following scheme of stimulation was used: stimulation of ipsilateral gastrocnemius-soleus and hamstring muscles during knee flexion (phase 1) and stimulation of tibialis anterior, hip adductors, quadriceps and gluteus maximus muscles during knee extension (phase 2).

Fig. 2. Examples of motor patterns during maximal voluntary knee flexion (left panels) and voluntary stepping movements (right panels) in the pre session. A – patient with FMS score =2. B – patient with FMS score =7. Note weak if any movements of the affected leg in both patients. Also, note the absence of EMG activity during MVC of the affected leg in patient 1 but its presence during stepping movements of the contralateral leg.

Fig. 3. Amplitude of MVC of knee flexors and extensors (A) and stepping-like movements (B) before and after treatment. Left panels represent absolute values (mean±SD). Right panels reflect amplitude increments after treatment (Δ=post-pre). Asterisks denote significant differences in the improvement of motor functions between the groups. C – pie charts showing the percentage of degree of paresis for each patient group before and after treatment. Note similar diagrams before treatment and significant shift towards light paresis after treatment in the experimental group.

Fig. 4. EMG activity of leg muscles during stepping-like movements before and after treatment. A – an example of EMG patterns (3 consecutive steps) in one patient. B – mean activity (±SD) of leg muscles during movements of the right leg in healthy subjects. Phase 1 –

knee flexion, phase 2 – knee extension. C – mean activity of leg muscles during movements of the paretic leg. Asterisks denote significant differences in mean muscle activity between pre and post treatment. D – the same analysis of EMG activity during movements of the non paretic leg. Note significantly higher BF activity of the contralateral leg in both groups of patients (B,C) compared to that in healthy individual (B).

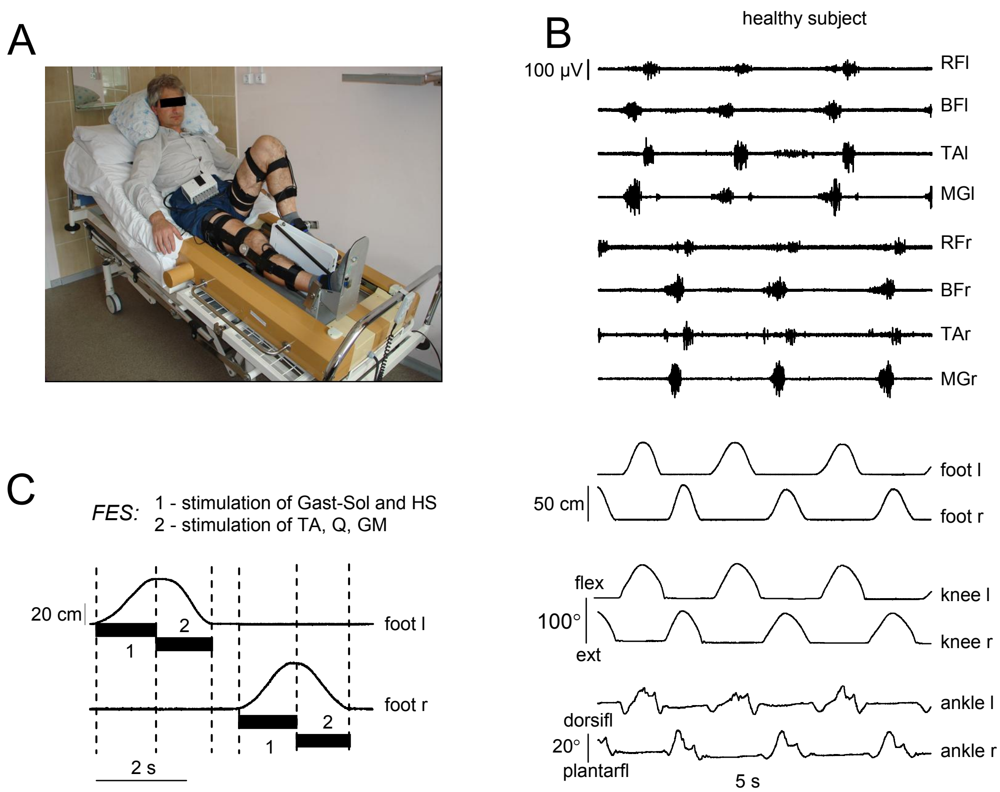

A
B
healthy subject
100 µV
RFl
BFl
TAl
MGl
RFr
BFr
TAr
MGr
foot l
50 cm
foot r
flex
knee l
100°
knee r
ext
ankle l
dorsifl
20°
ankle r
plantarfl
5 s
C
FES:
1 - stimulation of Gast-Sol and HS
2 - stimulation of TA, Q, GM
20 cm
foot l
foot r
1
2
2 s

Fig. 1

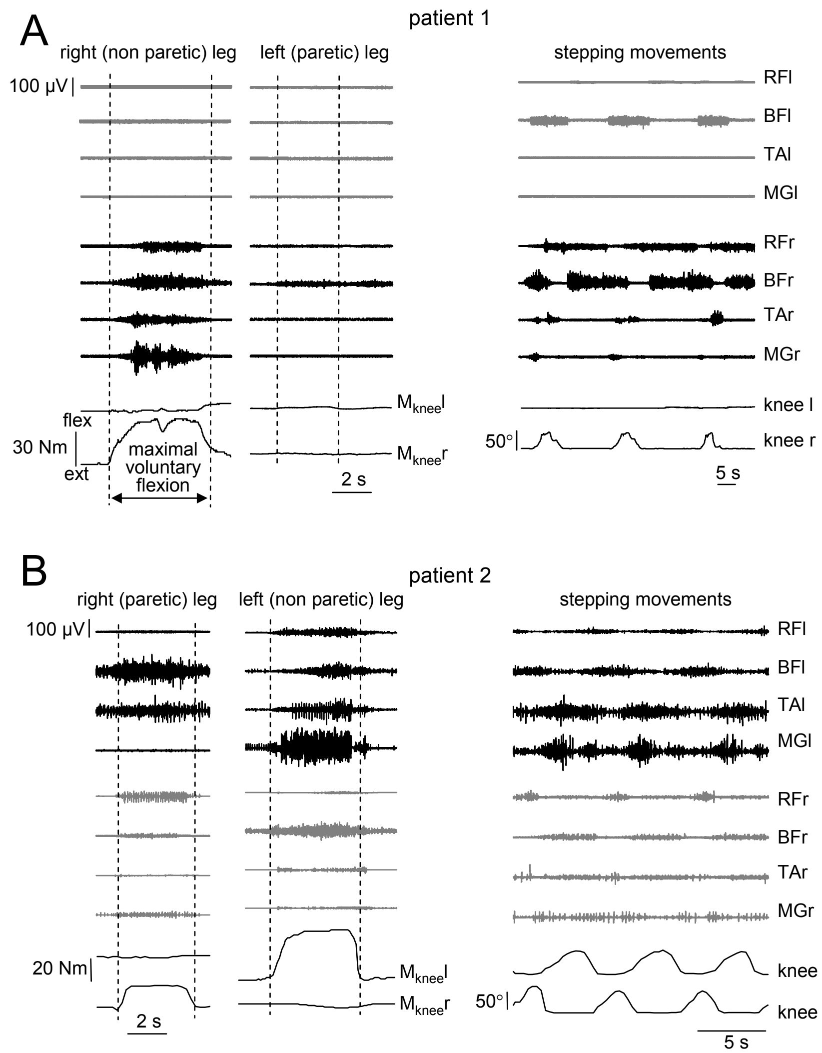

A
patient 1
right (non paretic) leg
left (paretic) leg
stepping movements
100 µV
RFl
BFl
TAl
MGl
RFr
BFr
TAr
MGr
knee l
knee r
flex
30 Nm
ext
maximal
voluntary
flexion
$M_{knee}l$
$M_{knee}r$
2 s
50°
5 s
B
patient 2
right (paretic) leg
left (non paretic) leg
stepping movements
100 µV
RFl
BFl
TAl
MGl
RFr
BFr
TAr
MGr
20 Nm
$M_{knee}l$
$M_{knee}r$
2 s
50°
knee l
knee r
5 s

Fig. 2

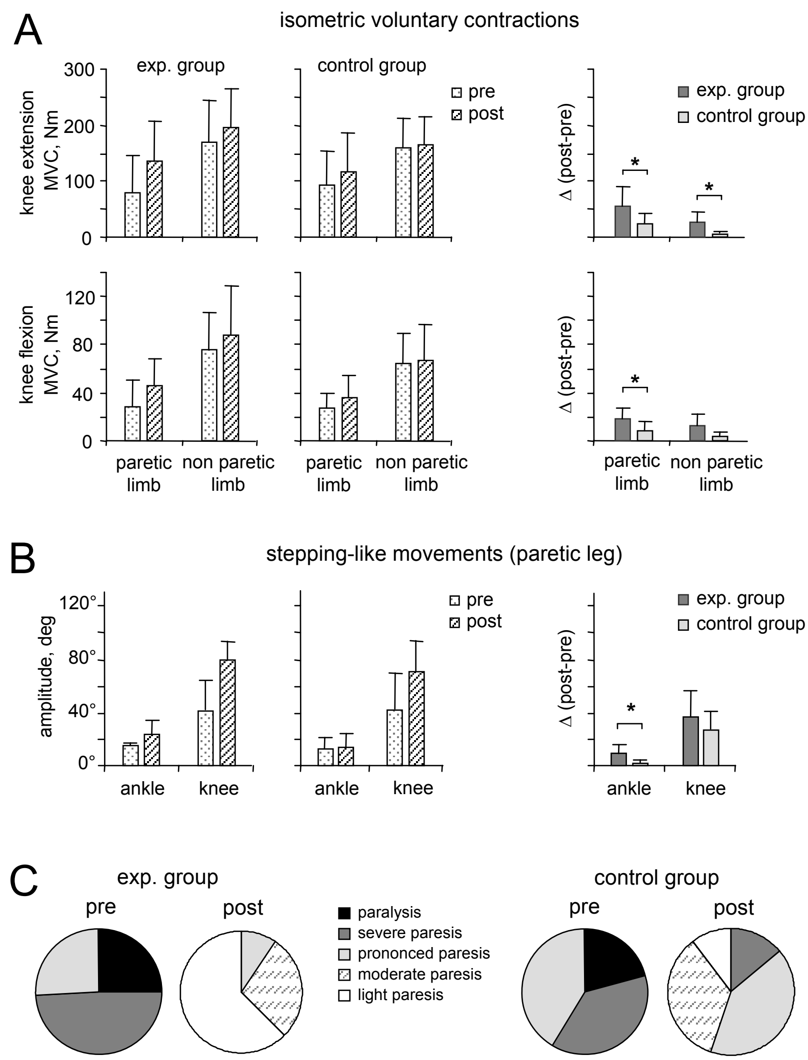
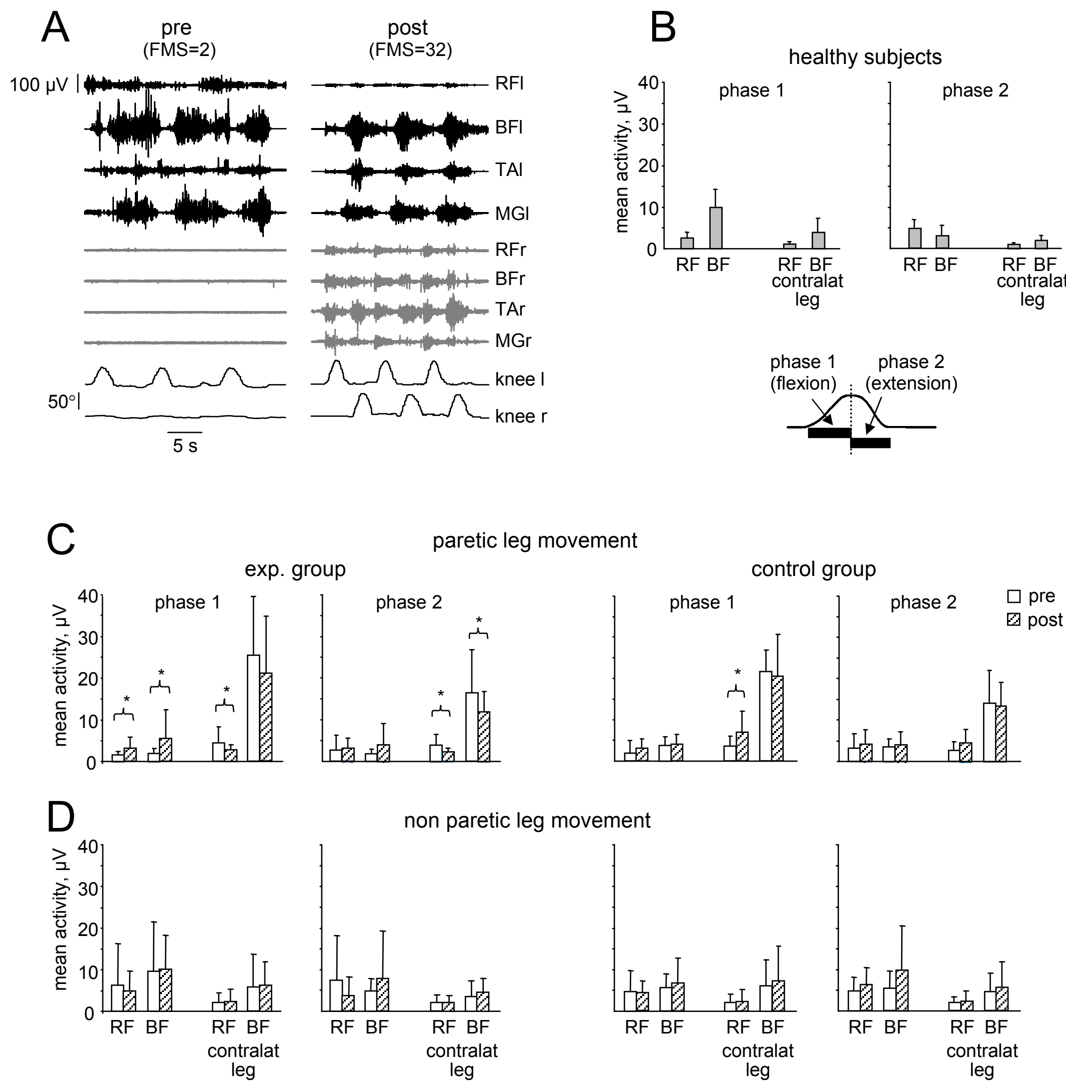

A
isometric voluntary contractions
exp. group
control group
pre
post
exp. group
control group
300
200
100
0
knee extension MVC, Nm
Δ (post-pre)
*
*
120
80
40
0
knee flexion MVC, Nm
Δ (post-pre)
*
paretic limb
non paretic limb
paretic limb
non paretic limb
paretic limb
non paretic limb
B
stepping-like movements (paretic leg)
pre
post
exp. group
control group
120°
80°
40°
0°
amplitude, deg
Δ (post-pre)
*
ankle
knee
ankle
knee
ankle
knee
C
exp. group
control group
pre
post
pre
post
paralysis
severe paresis
prononced paresis
moderate paresis
light paresis

Fig. 3



A
pre
(FMS=2)
post
(FMS=32)
100 µV
RFl
BFl
TAl
MGl
RFr
BFr
TAr
MGr
knee l
50°
knee r
5 s
B
healthy subjects
phase 1
phase 2
mean activity, µV
40
30
20
10
0
RF BF
RF BF
contralat
leg
phase 1
(flexion)
phase 2
(extension)
C
paretic leg movement
exp. group
control group
phase 1
phase 2
pre
post
mean activity, µV
D
non paretic leg movement
RF BF
RF BF
contralat
leg

Fig. 4