7 Functional Electrical Stimulation to Improve Mobility

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7.1 Introduction

Stroke is the most common cause of permanent disability in adulthood. Every year, 15 million people worldwide suffer a stroke, and about one-third have consecutive residual motor deficits [1]. Regaining the ability to walk after a stroke is a primary goal for many of those affected and thus an essential aspect in stroke rehabilitation [2, 3]. A large proportion of stroke patients, about 50%, have no walking function in the acute phase and about 12% require assistance to walk in the acute phase [4]. About 60% of initially non-ambulatory stroke patients are able to walk independently after 3 months of training in a rehabilitation facility, compared with only 39% of stroke patients treated in an acute facility. This evidence emphasizes the need for specific rehabilitation after stroke [5].

Gait deficits after stroke include a range of spatial, temporal, and kinematic deviations from normal gait, such as reduced speed, prolonged stance phase on the unaffected leg, reduced hip, knee, and ankle flexion during swing phase, and reduced knee extension and ankle stability during early stance on the affected leg [6]. Gait-oriented training is often used after stroke and it has been shown that, above all, walking speed and walking distance can be increased or enhanced by specific training [7]. Training of lower limb paresis after stroke typically consists of physiotherapy with the aim of strengthening the muscles of the lower limb, walking on different surfaces, walking on a treadmill as well as balance and coordination training [8–13].

About 10–20% of stroke patients who are able to walk again suffer from insufficient forefoot elevation in the swing phase on the affected leg – a so-called drop-foot when walking – and are consequently limited in their walking speed and distance and thus in danger to fall. Affected by a so-called “drop-foot“and the associated difficulties in walking are not only stroke patients, but also patients after brain injury, after spinal cord injuries and with multiple sclerosis [14].

Supporting the gait-oriented training described above, functional electrical stimulation (FES) of the peroneal nerve has been increasingly frequently used since its introduction by Liberson et al. (1961) [15]. Several studies support the motor remission of lower limb paresis after stroke by daily use of FES of the peroneal nerve [16–18]. FES is applied for weakness of forefoot elevation after stroke, in multiple sclerosis, after traumatic brain injury, and in traumatic paraplegic syndromes, among other conditions [19].

In the following chapter, in addition to the application of the FES, the effect on functional mobility induced by functional electrical stimula-

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tion of the peroneal nerve will be reflected on the basis of both semiquantitative and quantitative gait parameters. In the description of the effect of the FES, the differentiation between the "orthotic" effect and the "therapeutic" effect induced by long-term use of functional electrical stimulation of the peroneal nerve should be taken into account.

7.2 Functional Electrical Stimulation of the Peroneal Nerve-Method

Compared to the beginning of FES of the peroneal nerve in the sixties, the indication is unchanged. The clinical indications for which FES is frequently used are listed in Table 7.1.

The FES of the peroneal nerve is used to actively support the locomotor sequence in the swing phase during walking. Single-channel stimulators or dual-channel stimulators are used depending on whether there is isolated or predominantly a weakness in dorsal extension of the foot or additionally a weakness in hip flexion during the swing phase.

The FES is triggered either by a foot switch (placed on the heel) or by an accelerometer (integrated into the cuff).

Table 7.1 Indications for functional electrical stimulation

	indications
FES of the peroneal nerve	stroke
	multiple sclerosis
	brain injury
	spinal cord injury
	infantile cerebral palsy

Lifting the heel off the ground activates electrical stimulation of the peroneal nerve and tibialis anterior muscle via the pressure-sensitive foot switch (wired or wireless), and stops electrical stimulation at the end of the swing phase when the heel is placed on the ground via the pressure-sensitive foot switch (Fig. 7.1).

The accelerometer acts in a similar way; electrical stimulation is triggered by bending the knee at the beginning of the swing phase and stopped at the beginning of the stance phase when the knee is extended (Fig. 7.2).

In order to achieve an optimal synchronization of the gait pattern, the adaptation of the stimulation parameters such as rising ramp, follow-up time and falling ramp according to the walking speed is important additionally to the pulse width (Fig. 7.3). The following principles should be applied: The higher the walking speed the lower the rise ramp and extension time should be. However, if there is spasticity at the initiation of the swing phase, the rising ramp should be lengthened. If there is instability in the affected ankle joint, both the extension time and the falling ramp should be lengthened to support the affected ankle joint in the stance phase.

The stimulation parameters commonly used for FES of the peroneal nerve are listed in their range in Table 7.2.

In all currently available stimulation devices, the frequently applied stimulation parameters are already preset – this simplifies the handling of the stimulators during the testing phase. An essential condition for long-term FES therapy is a positive response in the testing of the FES of the peroneal nerve.

7.3 Effect of Functional Electrical Stimulation on Mobility

The efficiency of FES in improving mobility has been repeatedly reported using gait parameters such as walking speed, distance traveled, cadence, and gait symmetry [20–22].

The effect of FES on walking speed and physiological cost index was investigated in 26 patients with drop foot of different neurological

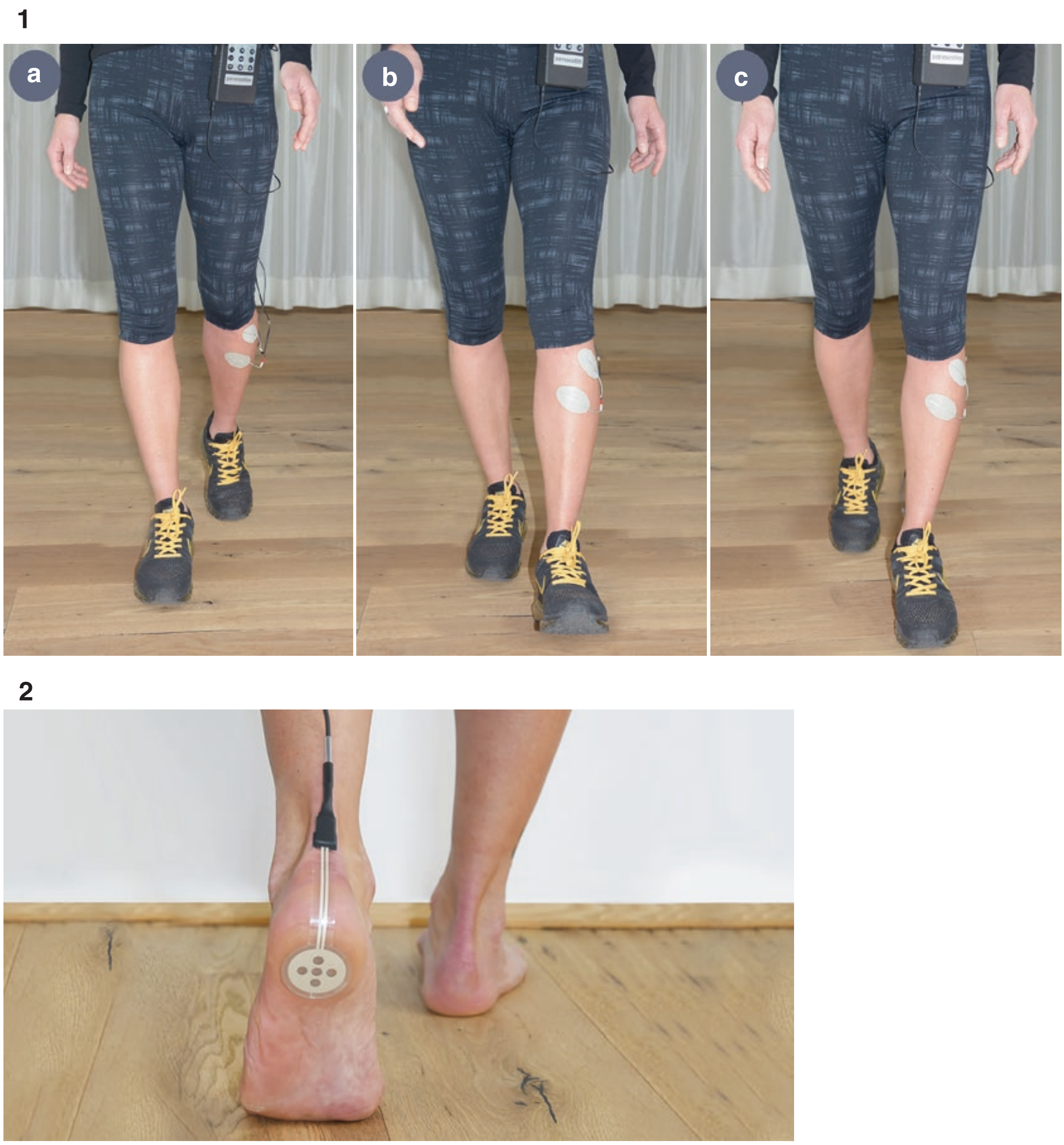

Fig. 7.1 (1) Application of the electrode over the peroneal nerve and the anterior tibialis muscle, shown in the initial swing phase (**a**), in the middle swing phase (**b**) and in the terminal swing phase (**c**); (2) foot switch is applied to the heel of the affected leg

etiologies: twelve stroke patients, six patients with traumatic spinal cord injury, two patients with traumatic brain injury, two patients with multiple sclerosis, two patients with brain tumor, one patient with hereditary spastic paraparesis, and one patient with infantile cerebral palsy (Stein et al. 2006). After a 3-month intervention period, walking speed and physiological cost index improved significantly both with and without FES.

In another study [19], in addition to gait parameters, the improvement in quality of life in 21 chronic stroke patients and 20 multiple sclerosis patients – induced by FES of the peroneal nerve – was examined. To document changes in quality of life, the Psychological Impact of Assistive Devices Scale was used. After an 18-week intervention period, the following results were obtained: in both intervention groups – stroke patients and patients with mul-

Fig. 7.2 A myoelectric orthosis-stimulates the peroneal nerve to lift the foot during the swing phase, utilizing a tilt sensor and accelerometer technology; shown in the stance phase (**a**), in the middle swing phase (**b**) and in the terminal swing phase (**c**)

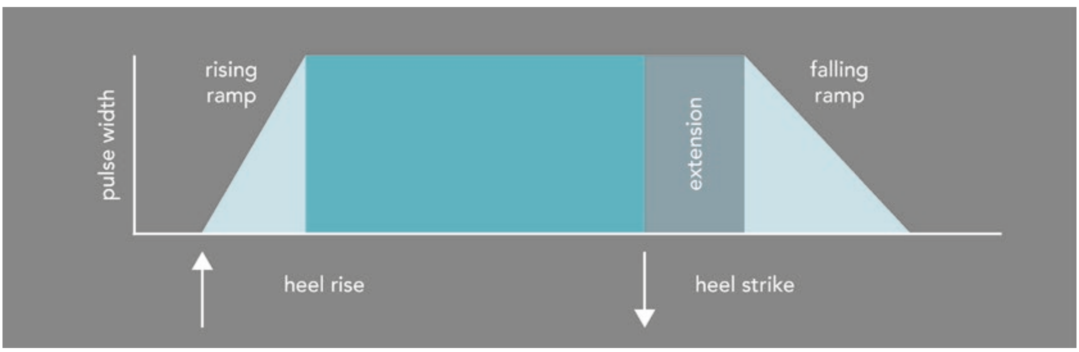

Fig. 7.3 Stimulation envelop for functional electrical stimulation: pulse width determines the extent of muscle contraction, the rising ramp allows the pulse width to swell slowly, the extension time prevents the foot from falling abruptly after heel striking at the end of the swing phase, and the falling ramp slowly reduces the pulse width to zero

Table 7.2 Stimulation parameters: μsec microseconds, Hz Hertz

FES of the peroneal nerve	
pulse shape	biphasic/rectangular
pulse width	220-300 μsec
frequency	20-60 Hz

tiple sclerosis – there was a significant increase in walking speed and a significant improvement in the domains of competence, adaptability, and self-esteem of the Psychological Impact of Assistive Devices Scale. Interestingly, the improvement in the domains of competence and adaptability was significantly greater in stroke patients compared with the multiple sclerosis group. Although FES leads to a significant improvement in quality of life, a correlation between objectively measured gait parameters and improvement in quality of life due to FES of the peroneal nerve could not be demonstrated.

The effect of FES combined with conventional therapy in chronic stroke patients (more than 3 months after acute event) was investigated in a prospective controlled intervention study [23]. Twenty-seven patients received the combination of FES with conventional therapy while twenty-four patients received conventional therapy without FES over an intervention period of 12 weeks. A significant improvement in spasticity, muscle strength, and Fugl-Meyer score of the affected leg could be observed after 12 weeks of intervention in the FES group compared to the control group. In addition to a significant increase in walking speed, a significant reduction in falls was further verified, which has a substantial relevance for everyday life.

In a randomized controlled trial of 102 chronic stroke patients (drop out of eight stroke patients), gait training plus FES was compared to standard therapy (ST) [18]. The primary aim of this study was to identify possible mechanisms responsible for the improvement in functional mobility. In both the FES group (54 patients) and the ST group (48 patients), the aforementioned interventions were performed on an outpatient clinic basis for 12 weeks. The 12-week intervention period consisted of a 5-week functional training phase (two 1-hour therapy sessions per week) and a 7-week post functional training phase (three additional one-hour therapy sessions during the remaining 7 weeks). During the functional training phase, patients were trained to use their treatment devices (FES or orthosis) for mobility at home, if necessarily with the prescribed walking device such as walking stick, etc. The content of the therapy sessions on device use was standardized across treatment groups. The effect of each condition, FES versus ST, was compared using kinematic and kinetic parameters of gait. Measurements were taken at the following time points: at the beginning of the intervention (t1), at the end of the 12-week intervention (t2), and at 12 weeks (t3) and 24 weeks (t4) after the end of the intervention. For all investigations including quantitative gait analysis (QGA), patients in the FES group did not wear a stimulator. In the ST treatment group, orthoses were allowed if already prescribed. In principle, orthoses were not prescribed for patients with mild weakness in forefoot elevation, orthoses were only prescribed for patients with significant weakness in forefoot elevation. A total of 86% of the 48 stroke patients in the ST group had orthoses prescribed in advance. Major findings to be stressed from this study are: both gait training with FES of the peroneal nerve and standard therapy resulted in improvements in hip flexion at the onset of swing and plantar flexion at the ankle during push-off, leading to significantly improved gait speed, cadence, and stride length. However, there were no differences between the two treatment groups. Interestingly, both treatment groups recorded a decrease in ankle dorsiflexion during the swing phase. For the authors, the clinical implications of this finding are unclear. A survey of all cited studies with single-channel stimulator is given in Table 7.3.

As mentioned above, in addition to dorsiflexion of the foot, hip and knee flexion may also be weakened during the swing phase. This will ultimately lead to a circumduction of the affected leg. In addition to the FES of the peroneal nerve, the quadriceps or biceps femoris muscle is further stimulated to support hip flexion and knee flexion, thus actively supporting the swing phase during walking. In this case, a dual-channel stimulator has to be applied.

The "orthotic effect" is basically understood as the prompt improvement of walking, directly induced by the FES, compared to walking without FES. A significantly higher walking speed under dual-channel stimulation (peroneal nerve plus biceps femoris or quadriceps muscles) compared with single-channel stimulation (peroneal nerve) was detectable objectively [24].

In another study, kinematic parameters of the lower extremity were examined in 16 chronic stroke patients after an intervention period of 6 weeks with dual-channel FES over the peroneal nerve and biceps femoris muscle [25]. Kinematic parameters were derived at baseline and after 6 weeks of intervention under the following conditions: Single-channel FES of the peroneal nerve versus dual-channel FES of the peroneal nerve and biceps femoris versus no FES. In nine patients with hip extension weakness, additional

Table 7.3 Survey of the cited studies with single-channel stimulation

authors	study	probands & intervention	duration of intervention	primary outcome	secondary otcome
Stein et al. 2006	cohort	26 P-FES	3 months	significant increased walking speed	significant increased physiological cost index
Barret and Taylor 2010	cohort	21 P-FES-S 20 P-FES MS	18 weeks	significant improvement in all domains of PIADS	stroke patients superior to MS patients
Sabut et al. 2011	PC study	27 P-FES-S 24 KT	12 weeks	significant increased walking speed and reduced falls	significant improvement of spasticity, muscle strength and of FM-Scores
Scheffler et al. 2015	RCT study	54 P-FES-S 48 ST	12 weeks	significant improvement of walking speed, cadence & stride length in both groups	no difference between the groups

biceps stimulation improved hip extension during the terminal stance phase. In seven patients with hyperextension in the knee, additional biceps stimulation resulted in a reduction of knee hyperextension during the stance phase and thus improved gait efficiency [25].

In a further study, 36 chronic stroke patients were investigated to what extent stroke patients with different walking speeds will benefit to the same extent from dual-channel FES [26]. Depending on walking speed, stroke patients were assigned to three different functional gait categories. Walking speed was investigated in a 2-min walking test with and without dual-channel FES. Testing was performed before the start of the study and after 6 weeks of daily application of the dual-channel FES application. Before analyzing the data, stroke patients were stratified into three functional movement classes according to their initial gait categories. It was found that dual-channel FES enhanced walking speed in all three functional gait categories. Stroke patients with limited ambulation at home improved their walking speed by 63.3%. In contrast, stroke patients with functional walking ability in the public domain improved their walking speed by only 25.5%. The authors concluded that dual-channel FES positively affects walking speed in stroke patients, regardless of initial walking speed. Furthermore, increasing walking speed with dual-channel FES may result in improving a person's walking status to a higher functional category [26]. A survey of cited studies with dual-channel stimulator is listed in Table 7.4.

Alternatively, the nociceptive withdrawal reflex (NWR), elicited by electrical stimulation on the sole of the foot can enhance dorsiflexion of the foot and, in particular, hip and knee flexion during the gait cycle and an improved stance phase on the other leg (Fig. 7.4) and results in a higher walking velocity.

Nociceptive withdrawal reflex-based FES supports gait training in the subacute and chronic post-stroke phase [27, 28].

Table 7.4 Survey of the cited studies with dual-channel stimulation

authors	study	probands & intervention	duration of intervention	primary outcome	secondary otcome
Springer et al. 2012	cohort	45 S P-FES versus P-BF-FES	6 weeks	walking speed with P-BF-FES significantly higher than with P-FES alone	
Springer et al. 2013	cohort	16 S P-FES versus P-BF-FES	6 weeks	walking speed with P-BF-FES significantly higher than with P-FES alone	improved hip extension in the stance leg phase & reduced knee hyperextension under P-BF-FES vs. P-FES
Springer et al. 2013	cohort	36 S P-BF-FES 3 FGK	6 weeks	walking speed improved by 63% in the case of limited walking ability when walking outside the home, the walking speed improved by 25.5%	

Although most of the FES studies have been conducted in chronic stages of neurological disease, it has been shown that FES of the peroneal nerve when applied in the acute stage leads to an improvement in motor function [29]. In a randomized controlled trial in 46 acute stroke patients – an average of 9 days after the stroke onset – daily 30-min FES was performed over a period of 3 weeks compared with placebo stimulation and a control group without stimulation. A total of 84.6% of patients in the FES group were able to walk after the intervention period, compared with only 60% of the placebo-stimulated group and 46.2% of the control group. Against this background, per se FES should not only be used in chronic stroke patients, but FES of the peroneal nerve should be a fixed part of early rehabilitation.

Recently, a systematic review of RCTs and crossover trials was performed to verify whether FES applied to the paretic peroneal nerve, combined or not combined with conventional therapy, could enhance gait speed in stroke individuals with drop foot [30]. The meta-analysis showed positive effects of FES on the peroneal nerve to improve gait speed when combined with physiotherapy while without physiotherapy no significant effect on gait speed was obtained. Nevertheless, the authors noted that because of the high heterogeneity in their analysis, they could not determine the benefits of FES combined with regular activities at home for improving walking speed [30].

7.4 Orthotic Effect Versus Therapeutic Effect of Functional Electrical Stimulation

FES of the peroneal nerve is intended to “normalize” gait, increase walking speed, and extend walking distance in patients with distally pronounced leg paresis by activating dorsiflexion in

Fig. 7.4 (1) Application of the electrode for eliciting the nociceptive withdrawal reflex during the gait cycle, in the stance phase (**a**), in the middle swing phase (**b**) and in the terminal swing phase (**c**); (2) the stimulation electrode is applied on the sole of the affected foot

the ankle during the swing phase. The “orthotic effect“is basically understood as the prompt improvement of walking, directly induced by the FES, compared to walking without FES. The “therapeutic effect” is understood as a long-term improvement in walking without FES compared to the initial examination without FES after the application of FES for several weeks [31].

The long-term effect and therefore the therapeutic effect of FES was already demonstrated in

2009 in a total of 16 stroke patients or traumatic brain injury patients [32]. After daily application of FES – for 12 months – all 16 patients improved significantly in walking speed compared to 2 months of daily application of FES and compared to prior to the start of FES. Interestingly, after 12 months of FES, even without FES, there was a significant improvement in all walking tests including walking over obstacles and carpet compared to testing prior to the start of 12 months of daily use of FES – compared to baseline without FES. Therefore, in addition to the quasi "orthotic" effect of the FES, the authors of the study postulate a therapeutic effect and state that the FES per se is superior to the peroneal orthosis in long-term use [32].

A recent study explored the presence of a long-term therapy effect of FES of the peroneal nerve in 133 chronic stroke patients [31]. To objectify a long-term therapy effect, the modified 10-minute-walking-test (10 MWT) was collected before the start of FES and on average after approximately 20 weeks of continuous use of FES. Twenty weeks after the start of the study, FES was still used by 124 patients (93%), with complete data sets finally available for analysis in 104 patients. The most common reason for excluding as many as thirteen patients from the analysis was insufficient length of stay to be able to perform all outcome measures. Nine participants had to be excluded because of cognitive dysfunction, and two because of problems with FES funding. Another two patients dropped out of the study because of pain while walking and two patients because of "inconvenience" caused by the FES. Only one patient discontinued the study because of repeated occurrence of leg spasms under FES. Skin irritation is one of the most common side effects of FES. Thus, minor transient skin irritation occurred in 12% of patients during the study. In all cases, FES could be continued without interruption. As a major finding, the study demonstrated a significant difference in walking speed without FES at baseline compared with walking speed without FES after 20 weeks of daily use of FES, thus demonstrating a treatment effect of FES with long-term use. An immediate initial orthotic effect at baseline and a total orthotic effect after 20 weeks of FES intervention were also significant. The authors interpret the results that the main benefit of FES of the peroneal nerve is the orthotic effect. However, the authors also note that a therapy effect is found with long-term use of FES of the peroneal nerve-especially in less-impaired stroke patients [31]. A survey of the cited studies on the therapy effect is given in Table 7.5.

The therapeutic effect of long-term use of FES is supported by the study of [33]. It was shown on the basis of neurophysiological parameters that after 12 months of daily FES application the maximum voluntary contraction of active dorsal extension increased by 48% in patients after stroke and by 17% in patients with multiple sclerosis, the amplitude of motor evoked potentials over the motor cortex increased by 50% in

Table 7.5 Orthotic effect versus therapeutic effect of functional electrical stimulation

authors	study	probands & intervention	duration of intervention	outcome – therapeutic effect
Laufer et al. 2009	cohort	16 S P-FES	12 weeks	walking speed without P-FES after 12 months of daily FES significantly higher compared with walking speed without P-FES at baseline
Street et al. 2017	cohort	104 S P-FES	20 weeks	walking speed without P-FES after 20 weeks of daily FES significantly higher compared with walking speed without P-FES at baseline

patients after stroke and by 27% in patients with multiple sclerosis. On the basis of the described results, the authors concluded: regular use of FES induces activation of the areas of motor cortex and residual descending corticospinal pathways. This may also be the explanation for the fact that after one year of daily FES, even without FES, walking speed is higher – in terms of the therapy effect – than before the start of FES [33].

7.5 Discussion

In conclusion, continuous single-channel and dual-channel FES leads to an economization of gait, a strengthening of the stimulated muscles, a decrease in spasticity and fall frequency, and an increase in stride length, walking speed, and endurance during walking.

Furthermore, an improvement in quality of life can be observed using long-term FES [19]. Moreover, daily use of FES leads to activation of cortical motor areas and residual efferent neural pathways [33].

Reflecting on the cited studies with single-channel FES, the direct effect of FES of the peroneal nerve in terms of significant increase in walking speed is always present when FES is switched on during end-tests [17, 19, 23, 34]. Only in the study by Scheffler et al. (2015), where the end-tests were performed without FES, a significant improvement in walking speed is shown in both the FES group and the standard therapy group, but no difference in the training effect of both groups [18]. The results found are related exclusively to the study condition performed in the study.

It must also be noted that dual-channel FES is superior to single-channel FES in all studies cited [24–26]. This effect is due to the fact that an isolated distally pronounced leg paresis is rather rarely present, but usually an additional weakness in hip flexion and knee flexion is present.

The differentiation between orthotic effect and therapeutic effect of FES should also be briefly discussed. It should be noted that in order to achieve a therapeutic effect and the associated activation of motor cortex areas and residual efferent corticospinal pathways, a daily long-term use of FES of at least 6 months is conditio sine qua non [31, 32].

Finally—reflecting the results of the application of FES of the peroneal nerve in acute stroke patients [29]—per se FES should not only be applied in chronic stroke patients but should be a part of early rehabilitation in acute stroke patients.

Summary

FES should not only be applied to chronic stroke patients, but FES should be an integral part of early rehabilitation in acute stroke patients.

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