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Enhancement of hemiplegic patient rehabilitation by means of functional electrical stimulation

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Abstract

This presentation will review briefly the current practice and state of the art in functional electrical stimulation (FES) as applied to stroke, head injured or brain tumour operated patients. A similar application is used in paretic patients following trauma or other aetiology. Over 20 years experience in the application of FES, as practised in Ljubljana, will be highlighted and the devices currently in use will be described. The statistics show the results obtained on 2,500 hemiplegic patients examined for FES application during the last 10 years. The statistics and results of the Slovenian population indicate 0.15–0.20% new cases annually or 1,500 new cases per million inhabitants. Up to 63% of annual cases are candidates for an FES based therapeutic locomotion rehabilitation programme. Experience indicates that 60% of hemiplegic patients received single-channel stimulation to correct equinovarus or foot drop, 30% obtained dual or even three channel stimulation treatment and only 10% of patients were involved in multichannel FES of four to six or even eight channels of stimulation. The benefits and outcome of rehabilitation will be presented and discussed in regard to current trends in the field of FES for hemiplegic and paretic patients. The partly inactive but very important field of FES application to the upper extremity in hemiplegic and paretic patients will be discussed and the relatively modest achievements presented. Future developments will be presented together with advances foreseen by steadily improving technology.

Introduction

For the last decade development in the field of functional electrical stimulation (FES) of hemiplegic patients was concerned with indications, prescriptions, treatment and modality refinements with important hardware improvements but no basic innovative developments taking place. The steady refinements and advances were a consequence of general technology improvements. The vital developments in the field of FES of spinal cord injured patients will dramatically, in the near future influence the field of hemiplegic patients. Due to the vast interest and overly optimistic expectations triggered in the early years of the last decade the major efforts of funding were focused on locomotion rehabilitation of spinal cord injured (SCI) patients utilising FES. It took almost 10 years to recognise and adopt more realistic and achievable expectations. Interest was regained in FES rehabilitation and methodology advances in the field of applications to stroke, head injury, trauma, surgical and other patients. The improved hemiplegia rehabilitation using FES is very important and promising. In terms of numbers of patients it by far exceeds the SCI field. Stroke is common in the middle-aged and elderly and brain injury is

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frequent in the younger and middle-aged population. Stroke affects two to three people per thousand and consequently dominates the field of neurologic rehabilitation. In the USA the population of hemiplegic patients is of the order of 2 million (LaPlaute, 1988). It is also interesting to note that for the last 10 years no significant advance has been made in the application of FES in the upper limb in general and in hemiplegic hands in particular. In contrast the rehabilitation of grasping and hand movement advanced noticeably in the field of quadriplegic patients. Developing technology and other advances in neural recording may in the future influence FES application in the restoration of hand function in hemiparetic patients following stroke, brain injury or operated brain tumour as described later in this presentation.

Before highlighting the advances and displaying the current state and trends in FES application for locomotion restoration in hemiplegic patients, the aims, goals and strategies in general will be presented since they are specific to the rehabilitation and use of FES in hemiplegic patients. Neurologic patients with upper motor neurone dysfunctions following stroke are considered as a stabilized or "complete stroke" group including by definition patients with cerebral thrombosis, infarction, embolus with infarction, intracerebral haemorrhage, the sequence of subarachnoid haemorrhage from aneurysm or arterio-venous malformation. Brain injured and/or operated brain tumour patients are also candidates for FES therapeutic treatment and later, if applicable, the long term use of FES devices for the restoration of lost function. All unstable or transient neurologic dysfunctions such as neurologic vascular episodes and stroke in progression are excluded from our consideration because by classical definitions (Davis, 1985) only patients suitable for rehabilitation are candidates for FES related rehabilitation treatment. After admission therapeutic FES application is focused on preserving existing function and augmenting recovery for restoration of lost function. A typical goal is to restrengthen weak muscles, maintain range of motion at joints and prevent the development of very exaggerated synergistic patterns such as extension or flexion patterns. At this stage spasticity development is reduced by FES treatment and the voluntary recovery of movement is enhanced. In general the goal is to facilitate sensory and antigravity awareness, to use the lower limbs for standing and to initiate early walking by the patient. Multichannel FES is very efficient in this respect and also helpful in lessening the physical effort by the physiotherapist in raising the patient to a standing position in the early phase of treatment. Early standing of patients is a good strategy ensuring faster recovery and preventing the development of severe spasticity with exaggerated synergism which is later very hard to modify. The described aims and goals of FES application follow the strategy of using in-patient hospital time efficiently to achieve a higher level of function in a shorter time. On completion such treatment indicates the lost functions which can be, at present, only partially restored by continuing FES. This is carried out in a programme of long term FES device prescription and patient training for independent home use. The following describes the current state of hemiplegic patient rehabilitation by means of FES as developed and practised in Ljubljana (Acimovic–Janezic, 1989; Malezic *et al.*, 1984; Stanic *et al.*, 1990). This will focus mainly on the lower limb programme utilising surface stimulation electrodes but also highlighting the upper limb applications.

Therapeutic FES applications

For the past 20 years the Ljubljana University Rehabilitation Institute has routinely practised FES as a treatment module additional to the standard and established therapy for rehabilitation (Acimovic–Janezic, 1989; Stanic *et al.*, 1990). At present about 80% of all patients admitted participate in the FES therapeutic or orthotic FES programme. With the help of electrical stimulation different muscles can be activated, restrengthened and the joint range of motion maintained actively, the blood circulation augmented and pain reduced. FES is a convenient and effective means of enhancing sensory awareness. In many instances mobilization is easier and achieved in a shorter time while also radically activating the patient's remaining and developing resources because FES provides afferent and FES induced movement with proprioception and exteroceptive sensory inflow. In hemiplegia particularly, the facilitation effect is important "reminding" the patient to exert the proper movement, enforcing maximal effort to perform it and hence leading to restoration in a shorter time. Repetitive movement stimulation is applied for lessening of contractures because of stretching effects and in many instances also moderates spasticity. Typical FES application indications are: to replace central lost control of movement by artificial FES control, to augment and learn a movement or to achieve a functional selective response of stimulated muscle groups, to break synergistic movement, patterns, to prevent development of contractures, to reduce spasticity and augment circulation. The early induced FES controlled pattern is selected to resist and prevent early indicated pathological synergistic pattern movement development. It also has the aim of producing a functional movement free of anomalies and as normal as possible. The therapist ensures that the obtained gait is repetitive, cyclical and symmetrical. The following muscle groups are accessible for surface stimulation for flexion, extension and eversion of ankle, knee flexion and extension and hip extension, abduction and by careful placement of electrodes also hip flexion (m. rectus femoris, m. tensor fasciae latae and m. sartorius). FES is used for gait assistance and to produce a movement pattern for relearning through repetition. The number of FES channels and the trigger mode selected is determined by the patient deficits, whether he can stand independently or has problems in rising. In the most severe cases where the patient is insecure in standing and is unable to take a step, usually 4 or up to 6 channels are applied and the physiotherapist is, at the beginning, triggering a preset pattern of muscle activation. After the patient progresses and repetitive stepping is achieved, the triggering can be accomplished by heel switches. Hardware is available for swing and stance phase triggering as well as adjustment of the set activation pattern dependent on walking rate. For patients with lesser anomalies or after they have progressed, the number of stimulation channels is gradually reduced to 2 or even only one. Typically recovery starts in the proximal joints and muscle groups and gradually progresses distally. The experience gained and results are best displayed by observing the statistical results. Figure 1 presents the epidemiological data for Slovenia (2.3 million). During the last ten years 2,500 patients were screened of whom 1,575 hemiplegic or hemiparetic cases were treated by FES. Some 2,000 patients were included in the FES programme and 425 received upper limb FES while the remaining 1,575 were candidates for the lower limb FES programme.

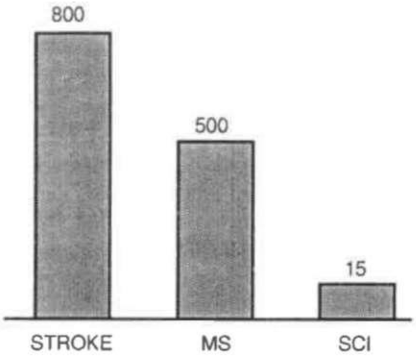

Figure 1. Epidemiological data of new cases per million inhabitants for Slovenia.

The treatment utilized and the division of patients in regard to applied number of FES channels is shown in Figure 2. In 60% of cases only one channel FES was indicated, 2 channels were indicated in 30% and in only 10% of cases multichannel and up to six channel FES was applied. It is interesting to observe the outcome for the single channel FES applications in respect of later continuing use (Acimovic *et al.*,

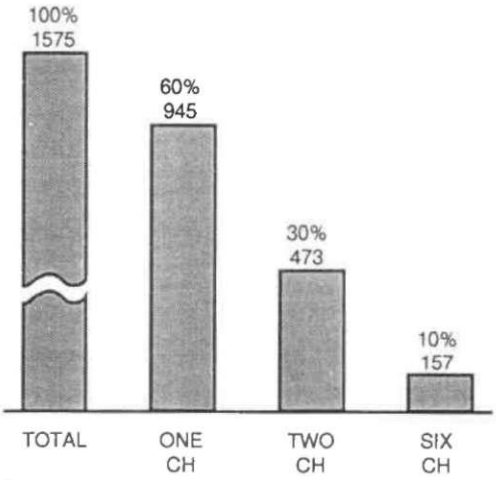

Figure 2. Statistical distribution of patients with regard to number of FES channels applied.

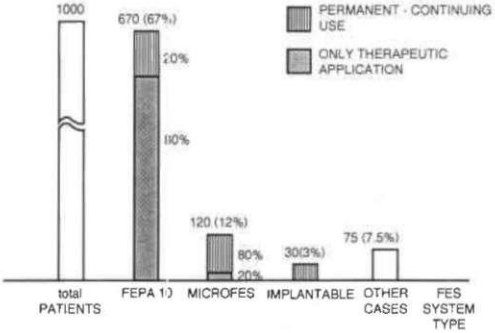

Figure 3. Single channel FES applications for equinovarus correction are presented in regard to device applied and resulting treatment outcome.

1987; Acimovic—Janezic and Kljajic, 1990). Figure 3 presents details of patients screened and treated in the last 10 years for equinovarus correction by single channel FES (peroneal brace). In 670 cases 80% of patients required only therapeutic FES, while 20% remained long-term users (FEPA 10[1] applications). In the last several years a smaller and more cosmetic system MICROFES[2] was applied (Acimovic *et al.*, 1987) and in the sample of 120 patients 80% of patients decided to use the system as a continuing assistive device in the home and only 20% used it solely for therapy.

This reversal of continuing usage is also the consequence of improved patient selection for the utilization of only a single channel (Bogataj *et al.*, 1990). In some patients, after they have used the surface unit for a year or more and expressed the wish for an implantable system, screening and testing is performed. Finally the implant (Acimovic *et al.*, 1987; Acimovic—Janezic and Klajic, 1990) is surgically placed in only 30 patients out of 1,000 cases, with a functional success of 96%. It should also be mentioned that for varying reasons, 75 patients did not receive any FES application but were treated by known conventional methods.

In the last several years the methodology of raising the patient to the vertical position and augmenting mobility in severely involved patients by means of six channel FES has been refined (Stanic *et al.*, 1990).

The goal of this treatment is to mobilize the patient as soon as possible and in cases of bilateral involvement two additional channels of FES are sometimes added. Figure 4 shows a patient equipped for 6-channel FES enabled walking in a later stage when he is already using bilateral crutches and shoe insole mounted trigger switches. The stimulation unit has provision for adjusting the polarity, timing, amplitude and triggering for each selected channel with regard to the function a particular and selected muscle has to provide. This radical therapy stimulation programme is applied for 2–3 weeks and later the number of channels is reduced gradually to 2 (Bogataj *et al.*, 1990) or even to just a single peroneal stimulator. The 6-channel unit and the new 2-channel unit incorporate rather advanced softwear embodying the knowledge collected over the last fifteen to twenty years. In Figure 5 the two channel stimulation unit is shown consisting of two main parts, the stimulator itself and the programmer-stride analyser unit (Bogataj *et al.*, 1990). The shoe insoles and the stimulation electrodes are not shown. This unit can usually be applied to activate a larger muscle group

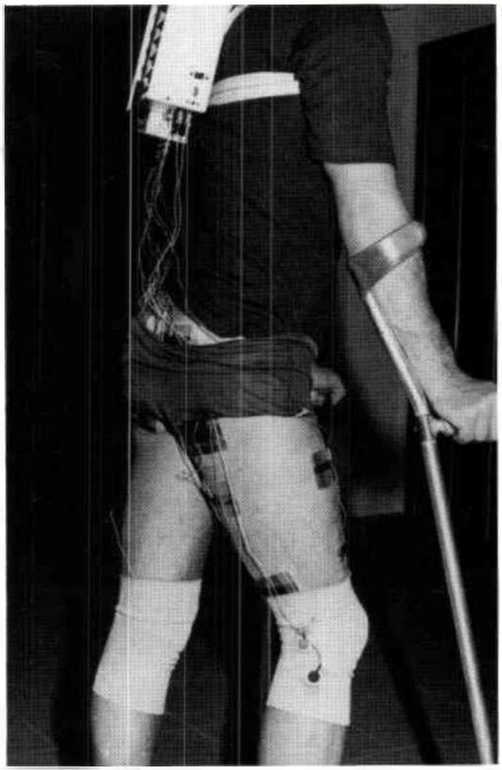

Figure 4. The patient is equipped for 6-channel FES therapy. The electrode locations are shown.

[1]FEPA 10 — Registered Trade Name by "Soca", Ljubljana.

[2]MICROFES — Registered Trade Name by Jozef Stefan Institute, Ljubljana.

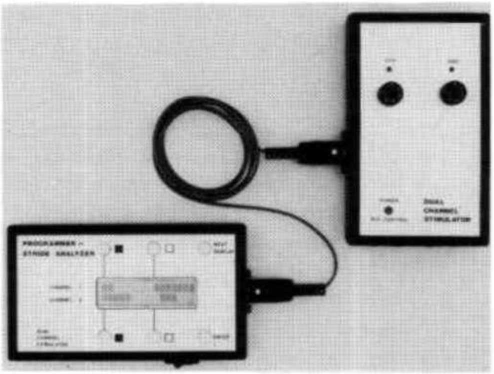

Figure 5. The 2-channel FES unit is displayed consisting of the unit worn by the patient and the programmer. The shoe-insoles and electrodes are omitted.

such as the m. quadriceps for knee extension, hamstring muscles for knee flexion or m. glueteus maximus for hip extension and the second channel is applied for peroneal nerve stimulation or to the pretibial muscle group for ankle dorsiflexion.

The 6-channel and 2-channel microprocessor based units also monitor and store data about patient gait performance. The measuring is performed on the basis of shoe insole switches. The statistics and average data of performance can be recalled at any instance after or during gait. The number of steps average heel on and off time are measured and recorded for both legs including the standard deviations (Bogataj *et al.*, 1990).

The programming unit enables user-friendly programming of the stimulator for the on/off time per channel in regard to the selected stance or swing phase trigger. The walking rate dependent (WRD) mode of stimulation or cyclical mode are available features. At the start of therapy the cyclical mode is applied while later the WRD mode allows the patient to choose his own preferred speed of gait with the stimulation sequence adjusted accordingly. The timing of the stimulation sequence of the patient's gait is based on a linear or weighted extrapolation of the previous four stride phase times. Three gradient dependable extrapolation equations are utilized and automatically selected and applied (Bogataj *et al.*, 1990). The patient's regained and restored functional ability after the 6-channel and later 2-channel treatment in most cases leads to the prescription of the single peroneal stimulator even in cases where possibly a 2-channel or even 3-channel device would be preferred. This is because at present no such 3-channel or 2-channel units are available for long-term use. Of course, the 2-channel unit can be prescribed for skilled and motivated patients, but in general the daily multi-electrode placement and fixation is too clumsy and the donning and doffing time-consuming and impractical. It is expected that in the future a suitable implanted system will be developed.

The FES therapy and methodology described is effective and is carried out for 8-10 weeks. Comparative studies (Malezic *et al.,* 1984) concluded that intense FES therapy advanced patient recovery to a higher level of function for almost the same medical personnel cost. As depicted in Figure 6, it is evident that the group treated by FES reaches a higher level of function, but on cessation of therapy slowly degenerates, gradually returning to the performance level of the control group treated by conventional rehabilitation methods. This indicates that FES devices such as the 2 or 3-channel continuous use units may be justified. Figure 6 also confirms that intensive FES locomotion restoration treatment for hemiplegic patients is cost effective and functionally more efficient if compared to the conventional treatment alone. It should be noted that FES intensive methodology shortens the time spent in hospital.

For the last ten years a rather passive stance was adopted in regard to FES application for hand and wrist function therapy with function restoration in hemiplegic patients. Recent interest in hemiplegic hand function restoration

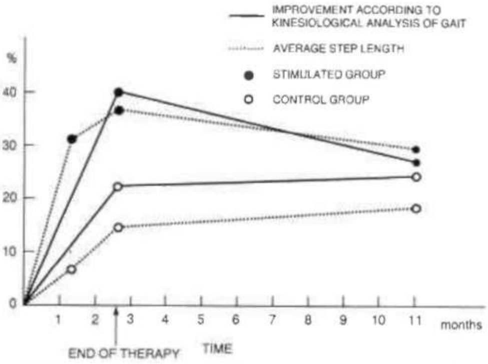

Figure 6. The course of functional progress utilizing the 6-channel FES system as compared in time of treatment to the classical rehabilitation therapy.

observed between 1970–80 has mostly faded out during the last decade. FES was applied at the end of the 1970s as a therapeutic means of effective treatment to improve the range of wrist and finger extension motions and to prevent the development of contractures caused by flexor spasticity. The application of cyclical isotonic FES of wrist and finger extensors decreases not only the established spasticity but also wrist and finger flexion deformities (Baker *et al.*, 1979). It was concluded that two to three 30–40 minute stimulation sessions per week could substitute for all other range of motion techniques. Patients gradually become accustomed to the feeling of discomfort caused by the treatment and the majority later learned to tolerate the sensation produced by stimulation even at the range of settings activating isometrically the wrist and finger extensors for a good, visible motoric response. Bowman *et al.* (1979) has proposed position feedback for automated treatment for the hemiplegic wrist by means of FES. The only marketed FES long-term wrist and finger extension system which is still available in Ljubljana was proposed nearly 15 years ago (Rebersek and Vodovnik, 1975). Because of the clumsiness in donning and doffing and the rather minor function of wrist and finger extension, the unit never reached comparable popularity when compared to the one-channel peroneal stimulator. The only FES system for continuing hand function restoration in hemiplegic patients is not a very successful unit. In spite of this the unit is still commercially available and is occasionally prescribed for therapeutic use. To our knowledge an implantable unit for hand function restoration in hemiplegic patients has not yet been produced or marketed. It is interesting, therefore, to present optimistic developments, because the future is going to progress first along the line of developing multichannel implants and these will also be very suitable for hand function restoration.

Trends and expectations

The FES methodology applied to hemiplegic patients for therapeutic treatment and gait assistance with long-term use for gait restoration has proven its effectiveness and usefulness (Malezic *et al.*, 1984; Stanic *et al.*, 1990). At present, of patients requiring long-term FES devices, only those who are candidates for simple equinovarus correction are reasonably well served. For this group of patients the single channel FES unit is available, being the only such unit in the market. In principle the equinovarus deficiency needs a balanced control of equinus and varus. This requires in essence a 2-channel unit. In addition up to now there has been negligible provision for the development of a total implanted system because the required technology was difficult to realize. The research results obtained within the last years have raised cumulative evidence that substantial progress can be expected towards the development of totally implantable systems. In principle the design of totally implanted systems is almost cosmetically ideal and eliminates patient donning and doffing.

In recent years refined recording techniques from sensory peripheral nerves (Johansson, 1991) indicate that with minimal circuitry for signal recognition it may be possible to develop very selective triggering and even provide control signals for arbitrary movement restoration by means of FES. These developments are complemented by long-term implantable infrafascicular recording electrodes (Lefurge *et al.*, 1991). These achievements are raising optimistic hopes that in the near future safe, reliable and good control using trigger signals can be obtained for hand and gait function restoration in hemiplegic patients, particularly with implanted systems. Continuous recording from peripheral nerves is very important, because these nerves are transmitting the information detected by natural sensors. For instance heel contact in gait can be detected and used for a trigger source.

Interesting developments have also begun to improve the motoric activation of muscles by FES and are also directly applicable to hemiplegic patients (Waters *et al.*, 1988; Marsolais *et al.*, 1990). Waters *et al.* (1988) are utilizing surgically inserted epimysial electrodes for therapeutic electric stimulation of the lower limb. By percutaneous wires, as used for almost two decades in the Cleveland upper extremities programme (Hunter Peckham, 1987) external connection to the epimysial electrodes is established. In patients with inadequate hip stability preventing them from balancing on one limb in order to take a step, FES assistance was provided (Waters *et al.*, 1988). The implanted epimysial electrodes enable the stimulation of hip joint extensor and abductor muscles. The results obtained indicated that the stimulation was effective for producing deep muscle contractions and that percutaneous stimulation was safe. A similar approach is described by Marsolais *et al.* (1990). They also applied the percutaneous wire electrodes (Hunter Peckham, 1987) for activating the muscles that provided the necessary functional improvement and progression from standing to stepping or walking. Muscle groups like m.erector spinae for torso control, gluteus maximus and medius, tensor fasciae latae, posterior adductor or others for hip control and biceps femoris, with quadriceps for knee function were implanted. The muscles of the ankle were also stimulated to the extent necessary to obtain the desired functional level. Improved walking was demonstrated in all five implanted patients (Marsolais *et al.*, 1990). Patients have complained about the wires connecting the shoe-insole switch as well as the electrode wires. They have also complained about the maintenance of the electrode sites where the percutaneous wires are penetrating the skin. The same technology so far described for the lower extremities utilizing percutaneous wires and epimysial electrodes for the FES programme, can be introduced immediately in hemiplegic patients for the restoration of hand function and grasp. The percutaneous system for hand function restoration in quadriplegic patients (Hunter Peckham, 1987) has already advanced to an implanted epimysial electrodes system and only the control signal set-up is preventing the development of totally implanted hardware. In Japan, Hoshimija *et al.* (1985) are reporting the development of a multichannel FES system for the paralyzed upper extremities using percutaneous wire electrodes. The system is similar in design to that used in Cleveland (Marsolais *et al.*, 1990; Peckham, 1987) where external hardware is used to provide the trigger or control signals. This short review indicates trends and signals exciting new possibilities for the future development of FES based hand function restoration hardware presently applied to quadriplegic patients. We believe that these advances will also particularly benefit hemiplegic hand rehabilitation. The expectations based on the described advances are also promising for the lower extremities FES programme in general. The recent accomplishments in peripheral nerves afferent signal detection is enabling the recording of signals from natural receptors providing ideal control and trigger sources for lower limb FES. These developments are realistic and are also supported by exciting designs of multichannel implantable FES systems being fostered by cochlear implants. These implants have already proved safe, and provide function and promising technological possibilities. Gradually the conclusion is growing that for the entire FES field the vital technological problems are reaching the stage where the hardware of the system will not present a problem, but rather the poorly developed knowledge of clinical application. From the presented discussion it is evident that also in hemiplegic rehabilitation the clinical methodology and application knowledge is going to be the limiting, decisive and costly factor. Summarizing the state of the art in hemiplegic FES it is justifiable to conclude that it is realistic to expect rising momentum and exciting new developments in this field.

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