

Chapter 9

Functional Electrical Stimulation Therapy: Individualized Neuroprosthesis for Grasping and Reaching

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Although conventional occupational therapy was ineffective, the client was able to grasp a soda can after four months of FES therapy.

Abstract Stroke and spinal cord injury clients experience permanent disability resulting in total or partial upper limb paralysis. The paralysis can be either unilateral (typical for stroke clients) or bilateral (typical for cervical spinal cord injury clients). Approximately 85% of people living with stroke have severe upper limb paralysis, while 45% of people living with tetraplegia have persisting upper limb motor deficits more than one year after onset. These persisting functional inabilities affect their independence in activities of daily living, thereby increasing their need for attendant care services. This chapter provides a discussion of available therapies, with a particular focus on functional electrical stimulation therapy (FES).

Keywords Grasping • Neuroprosthesis • Reaching • Stroke • Spinal cord injury

Definitions

Reaching refers to abduction or flexion of the arm with an extended elbow to shoulder height.

Grasping refers to both palmar grasp and lateral prehension. *Palmar grasp* refers to opposition of the thumb and palm followed by flexion of the thumb and fingers, and is used to hold a water bottle. *Lateral prehension* is generated by flexing the fingers to provide opposition followed by thumb flexion, and is used to hold light objects like keys or paper.

Functional electrical stimulation (FES) is provided by a group of devices, conventionally prescribed for lifetime use, in which an electrical current is applied to a muscle or group of muscles via implanted or surface electrodes to stimulate the client's paralyzed muscles to contract and perform functional or leisure activities that are not otherwise possible.

In functional electrical stimulation therapy (FES-T), FES is applied intermittently for short periods of time (2 to 6 months) to elicit or augment voluntary upper limb motor function.

Purposes

Functional electrical stimulation therapy is an intervention to improve grasping and reaching in clients with stroke or spinal cord injury (SCI) and weak or paretic upper limbs.

Method

Candidates for Functional Electrical Stimulation Therapy

Acute or chronic stroke and SCI clients with upper limb impairments and an inability to voluntarily grasp or reach objects with the impaired limbs are candidates for FES-T.

Epidemiology

Implanted FES systems have conventionally been used in clients with acute tetraplegia. Surface FES systems have been used in the past as an orthotic system prescribed for long-term substitution for inadequate or absent upper limb motor function in clients with stroke or SCI. This chapter outlines the paradigm shift in using FES as a short-term therapeutic tool to improve reaching and grasping in clients with stroke or SCI and absent/inadequate upper limb function prior to FES-T.

Settings

The studies presented and discussed were conducted in tertiary stroke and SCI rehabilitation centers or university-affiliated academic institutions in Canada, the United States, and Europe.

The Role of the Occupational Therapist

Occupational therapists (OTs) are responsible for identifying clients who are candidates for FES-T, for providing FES-T, and for evaluating its effectiveness. The OT advocates for FES-T resources in the practical environment.

Results

Clinical Applications

Overview of Current Grasping and Reaching Therapies

Constraint-induced intervention (Page and Levine, 2007; Wolf et al., 2006), neuro-modulation of the motor cortex in stroke clients (Petrofsky and Phillips, 1984), robotics-assisted therapy (Nef et al., 2007), and FES-T (Popovic et al., 2005) are currently being explored as interventions to minimize upper limb impairments. Among these, the most promising is FES-T for promoting or restoring grasping and reaching.

Functional Electrical Stimulation Devices (Apparatus)

Commercially available FES systems to restore grasping based on the former FES concept of substituting for motor impairment are the Freehand system (Mulcahey et al., 2004) and the Handmaster or Bioness H200 (Alon et al., 2007). The Freehand system is an implanted system primarily used in clients with SCI, while the Bioness H200 has been used in both SCI and stroke clients.

Functional Electrical Stimulation Versus Functional Electrical Stimulation Therapy

Functional electrical stimulation devices produce muscle contractions or sequences of contractions generated by a microprocessor-controlled electric stimulator. This enables controlled stimulated sequences of functional activity such as grasping or releasing a cup. Functional electrical stimulation was previously prescribed for lifetime use throughout the day to substitute for a motor activity the client could not perform.

In contrast, FES-T refers to a group of novel therapies in which FES is applied intermittently for a short period (2 to 6 months) to elicit and or augment voluntary upper limb motor function. Electrical stimulation applied during FES-T is delivered using short electrical pulses, preferably current regulated balanced biphasic pulses that generate a sequence of action potentials of adequate amplitude in the peripheral nerves. Visible or palpable muscle contractions are elicited. FES-T is individualized for the client and can be delivered using surface, transcutaneous, percutaneous, or implanted electrodes, with surface electrodes predominating. The choice of FES versus FES-T should be based on the client's goals, prognosis, and resources.

Use of Surface Versus Percutaneous Electrodes

Surface electrodes are inexpensive and easy to apply to the skin, but they are ineffective when stimulating some peripheral nerves (i.e., those innervating the proximal

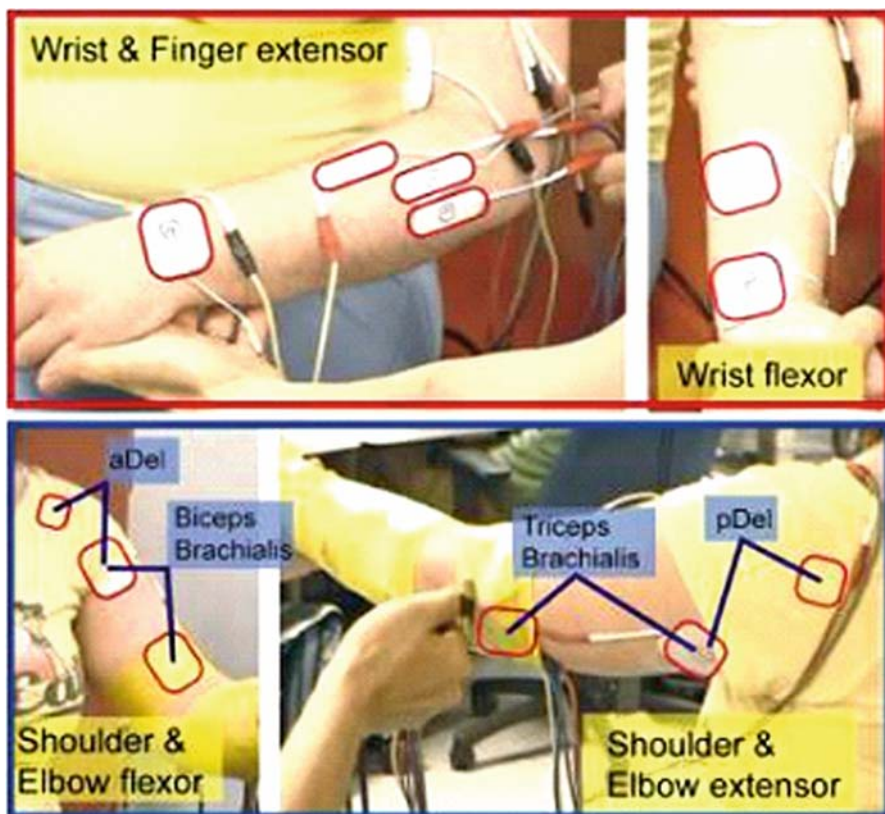


Fig. 9.1 Typical locations of the surface stimulation electrodes that are used to retrain reaching and grasping functions.

shoulder muscles). The typical locations of FES-T electrodes for grasping and reaching are shown in Fig. 9.1.

Percutaneous electrodes consist of thin wires that are inserted through the skin into the underlying muscle tissue where they remain in place up to 30 days.

Implanted electrodes are permanently implanted in the muscle or around a peripheral nerve. BION™ microstimulators (Advanced Bionics Corporation; Valencia, CA) are implanted via a hypodermic needle (Loeb, 2003); they are cylindrical in shape (2-mm diameter and 16-mm length), and are powered and controlled via radio waves from an external controller carried by the client.

Compared to surface electrodes, implanted and percutaneous electrodes have higher stimulation selectivity with much less electrical charge applied, both of which are desired characteristics. Implanted electrodes, with the exception of the BION, require lengthy surgical procedures to implant. In contrast, percutaneous

electrodes are used temporarily. Implanted and percutaneous electrodes may cause local infection.

Functional Electrical Stimulation Therapy Intervention

Functional electrical stimulation therapy is typically applied using surface electrodes three to five times per week for 12 to 16 weeks with each session ranging in duration from 30 to 60 minutes.

Evidence-Based Practice

In an evidence-based practice, OTs perform standardized assessments to characterize the client's impairment and disability, identify subgroups suitable for specialized care, and assess treatment efficacy. The choice of the standardized assessment is dictated by the intent of the assessment. The Chedoke McMaster Stages of Motor Recovery (CMSMR) is an example of a valid measure with sound psychometric properties used to describe upper limb function after stroke and to help determine a prognosis. Less than 10% of stroke clients with CMSMR stages 1 or 2 recover their reaching and grasping ability (Rand et al., 1999). The reader is encouraged to become familiar with the assessments described herein for stroke and SCI clients.

The recent paradigm shift from using FES technology as an orthotic system to using it as a therapeutic tool to improve strength in clients with barely perceptible or weak voluntary upper limb motor function has resulted in improved voluntary reaching and grasping. Extensive experiments and investigations using FES-T as an intervention have been conducted by researchers around the world (Burridge et al., 2007; Gritsenko and Prochazka, 2004; Popovic et al., 2002, 2003, 2004), and by the authors' team (Popovic et al., 2005, 2006)

Surface Functional Electrical Stimulation Therapy for Stroke Clients

Many authors have experimented with surface FES-T systems over the last 5 years to restore grasping in stroke clients (Popovic et al., 2002, 2003, 2004). These studies categorize stroke clients based on their functional ability into high or low functioning groups. The high functioning group (HFG) subjects (four FES-T and four controls) (Popovic et al., 2002) could actively extend the affected wrist ≥ 20 degrees, and extend their metacarpophalangeal (MP) and interphalangeal (IP) joints of all digits 10 degrees prior to FES-T. The low functioning group (LFG) subjects (four FES-T and four controls) (Popovic et al., 2002) could extend the paretic wrist < 10 degrees, and volitionally extend the MP and IP joints of the thumb and two other digits for < 10 degrees prior to FES-T.

Functional electrical stimulation therapy was applied daily for 3 consecutive weeks, up to 30 minutes per session. Controls received conventional physical therapy and OT. In the first and consecutive studies the Upper Extremity Functioning Test (UEFT) (Popovic et al., 2002) was used to assess subjects before and after FES-T. In later studies, the sample size was increased to 38 acute subjects (22 FES-T and 16 controls), and the controls were invited 12 months post-stroke to participate in the FES-T as well as the chronic clients (Popovic et al., 2003, 2004). In these later studies the UEFT, Drawing Test (DT), and the Modified Ashworth Spasticity (MAS) Scale were used to assess subject outcomes.

In all studies, acute subjects were assessed 12 months after enrollment in the study and chronic subjects up to 23 weeks after enrollment. Results of these three studies suggest that both acute and chronic stroke clients benefit from FES-T. Both the HFG and LFG benefited from FES-T, but the HFG had greater benefits and are best suited for FES-T.

Gritsenko and Prochazka (2004) used a sophisticated workstation with multiple instrumented objects typically used in activities of daily living in concert with a modified-impact cuff FES system to generate hand opening and closing. Six stroke clients (three males/three females), >12 months post stroke, participated; all had reasonable range of shoulder and elbow active range of motion, but were unable to grasp and release objects.

Functional electrical stimulation therapy was administered on 12 consecutive weekdays. The sessions were 1 hour long, during which subjects performed three tasks for 20 minutes each. Subjects were assessed on admission, on discharge, and 72 days after admission (follow-up), using the Fugl-Meyer Assessment (FMA) and Wolf Motor Function Test (WMFT) kinematics. Kinematics were assessed using the instrumented objects on the treatment and assessment days. WMFT and kinematic assessments showed improvement during treatment and on discharge, but were lower on follow-up assessment. The FMA scores did not improve. Functional electrical stimulation therapy in conjunction with an instrumented workstation was associated with improvements in hand function among hemiplegic stroke clients whose level of motor function would have precluded them from constraint-induced therapy.

Burridge et al. (2007) used an implanted FES system, the BION microstimulators, to help seven chronic (>12 months) stroke clients (four males/three females) improve voluntary hand opening and closing with CMSMR baseline stages 4 and 5. Subjects were assessed using the Action Research Arm Test (ARAT), Tracking Index (TI), and FMA assessments on admission and after 12 weeks. Functional electrical stimulation therapy was administered once or twice daily for at least 12 weeks. The ARAT, TI, and FMA showed improvements. However, the data presented were preliminary in nature, and future publications of the results are expected.

Our team (Popovic et al., 2005) is the first group to apply FES-T to restore voluntary reaching and grasping in severely impaired stroke subjects. These subjects were at CMSMR stages 1 or 2 at baseline, considerably lower than subjects in similar studies. Thirteen acute stroke subjects participated in a randomized control trial (five FES-T and eight controls) where FES-T for reaching and grasping was administered

for 12 to 16 weeks, three to five times per week, 45 minutes per session. Controls received conventional PT and OT. Subjects were assessed on admission and discharge using the Functional Independence Measure (FIM), Barthel Index (BI), CMSMR, FMA, and Rehabilitation Engineering Laboratory Hand Function Test (REL test) (Popovic et al., 2005).

Statistically significant results were achieved on all tests, except FIM in favor of FES-T. FIM was not sufficiently responsive to capture improvements in arm and hand function during the study. When statistically significant results are achieved with extremely low number of participants (five FES-T and eight controls) this suggests that the administered intervention, in this case FES-T as compared to conventional PT and OT, ($p < .05$) is beneficial and merits further investigation. Our study also included detailed electrophysiologic examinations of selected subjects (article in preparation), which revealed that muscles with tone prior to the FES-T had significant tone reductions, and muscles that subjects were unable to relax or contract voluntarily prior to the intervention, were able to do so following FES-T.

Surface Functional Electrical Stimulation Therapy for Clients with Spinal Cord Injury

Our team conducted an randomized controlled trial (RCT) in which surface FES-T was applied to clients SCI as a treatment to improve grasping function (Popovic et al., 2006). Ten subjects with complete SCI (six FES-T and four controls) and 11 individuals with incomplete SCI participated (six FES-T and five controls) (Fig. 9.1). The subjects were assessed using the FIM, SCIM (Spinal Cord Independence Measure), and REL tests. Although the results to date are not statistically significant, they suggest that FES-T improves grasping in clients with motor complete or incomplete SCI as measured by the FIM, SCIM, and REL tests.

Discussion

Functional electrical stimulation therapy has the potential to improve reaching and grasping in clients with stroke and SCI.

The key factors to ensure FES-T success include (1) application early after the onset of stroke or SCI; (2) use of FES in conjunction with conventional physiotherapy or occupational therapy; (3) incorporation of customized electrical stimulation protocols, and programmable FES systems are required; (4) therapies that are delivered with the FES system; (5) repeatable yet diverse activities should be administered; and (6) FES-T administration for at least 40 minutes, three times per week is essential as this dose improves both reaching and grasping in clients with stroke and SCI.

The functional gains anticipated with FES-T are greatest in clients with acute stroke or SCI but are evident in both acute and chronic clients. This review

summarizes the published benefits of FES-T among clients with stroke or SCI. The generalization of the findings are limited by small sample sizes, individualized treatment and outcome assessment protocols, diverse inclusion criteria, and the availability of FES-T equipment and OT expertise in clinical as opposed to research settings.

The OT and resource requirements associated with FES-T, although significant, have the potential to improve SCI and stroke clients' functional abilities and reduce the burden of care over their lifetime.

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