
Functional Electrical Stimulation Therapy for Grasping in Spinal Cord Injury: An Overview

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Upper limb rehabilitation strategies for individuals with spinal cord injury (SCI) have evolved greatly over the last few decades. Amongst these strategies, functional electrical stimulation (FES) approaches have been widely recognized as the most promising. To date, 2 FES-based approaches for improving upper limb function in individuals with SCI have emerged. One approach proposes the use of FES as a permanent orthotic device that patients have to use all the time to grasp and release objects. In this application, the FES systems for grasping are better known as neuroprostheses for grasping. The second approach has emerged only recently, and it proposes the use of FES as a short-term therapeutic intervention with an objective to help the damaged central nervous system relearn how to execute the grasping function voluntarily. More specifically, after the therapy is completed and the FES system is permanently removed, the patients are able to grasp and release objects on their own, that is, without the help of FES device. In its first embodiment, FES technology is used as a permanent orthosis; in its second embodiment, it is used as a therapeutic tool. **Key words:** functional electrical stimulation, functional electrical stimulation therapy, neuroprosthesis, retraining voluntary function, spinal cord injury, upper extremity rehabilitation

To date, most of the clinical work in the functional electrical stimulation (FES) field has been done at the level of proof of principle studies and pilot randomized control trials. As a result, many clinicians have been hesitant to introduce FES treatment as a new standard of care. However, this notion about the FES technology has been changing rapidly due to mounting evidence that FES can profoundly improve hand function in tetraplegic individuals. The purpose of this article is to draw the attention of the reader to a series of clinical publications that our team has published in last 10+ years that discuss the FES therapy for grasping for individuals with tetraplegia. The final article in the series presents the findings of a randomized control trial that demonstrates that FES therapy for grasping is an effective method to restore voluntary hand function in individuals with tetraplegia.

Introduction

The use of electrical stimulation to induce/promote functional recovery in individuals with neurological impairments was first introduced in early 1960s by Liberson and colleagues.¹ They developed an FES system that stimulated the common peroneal nerve to correct drop foot. Following that, a series of FES systems were developed – FES to improve grasping, reaching, standing, walking, hearing, coughing, and bladder voiding.² Over the past 5 decades, a series of FES-based technologies have been developed and commercialized.

One FES technology that has attracted a lot of attention since 1980s is neuroprosthesis for grasping. Among persons with cervical spinal cord injury (SCI), restoration of hand function is a key priority.³ Although many therapies, surgical interventions, and devices have been proposed over the years to improve hand function in individuals with C4-C7 SCI, one technology clearly stands out in its ability to restore upper limb function – FES technology for grasping.⁴⁻¹⁰

The FES systems for grasping are able to restore power grasp and precision grip.¹¹ Power grasp is used to hold larger and heavier objects between the palm of the hand and the 4 fingers. During a power grasp, the object is held in a clamp formed by partly flexed fingers and the palm, counter pressure being applied by the thumb lying more or less in the plane of the palm.¹¹ Precision grip is used to hold smaller and thinner objects, such as keys and paper, between the thumb and forefinger. The precision grip is generated by flexing the fingers followed by opposition of the thumb.¹¹

In one application, the FES systems for grasping are permanent orthotic devices that patients have to use all the time to grasp and release objects.^{4,10,12} In this application, the FES systems for grasping



Figure 1. Example of object manipulation during FES therapy.

are better known as neuroprostheses for grasping. The neuroprostheses for grasping can either be implanted or surface FES systems. The FES systems for grasping can also be used as a short-term therapeutic intervention.^{8,9,13-15} In this application, the FES systems are not used as permanent orthotics, rather the patients use them as a short-term therapeutic intervention to restore voluntary hand function.^{8,9,13-15}

In essence, short-term therapeutic FES systems are used to promote functional and purposeful recovery of the hand. During therapy, the FES systems assist the individuals with SCI to grasp and release objects. As the patient slowly regains hand function, he or she is gradually weaned off the FES system; eventually the user who is trained with the FES system is able to grasp and release objects voluntarily without the FES device.

In what follows, we present a summary of the findings that our team has published pertaining to the use of FES systems for grasping as a therapeutic tool to restore voluntary hand function. This therapy is known as FES therapy or FET.

Complex Motion Stimulator

In this section, we focus on the use of FES to restore voluntary grasping following SCI. As discussed earlier, different FES systems for improving grasp function have been developed and evaluated to date. Some notable devices are Bionic Glove (University of Alberta, Canada),^{6,14} NESS H200 (Bioness Inc, USA),¹² Belgrade Grasping System (University of Belgrade, Serbia),¹⁶ and Freehand system (Freehand system is the only implantable device formally manu-

factured by NeuroControl Corporation, USA),¹⁰ The benefits and shortcomings of each of these systems are extensively discussed in literature.⁷ In 2001, our team¹⁷ introduced a custom-made neuroprosthesis that was developed using the Complex Motion Stimulator (Complex SA, Switzerland). The Complex Motion Stimulator is a multi-channel FES system that can be used for various electrical stimulation applications. The Complex Motion system consists of a portable stimulator with a programmed chip card, self-adhesive stimulation electrodes, and various man-machine interfaces, such as push buttons, sliding potentiometers, accelerometers, Complex EMG/biofeedback sensor, joysticks, foot switches, the gait phase detection system¹⁸ and a brain-machine interface.¹⁹ The programmable chip card allows for most of the stimulation parameters and user interfaces to be adjusted based on individual patient requirements. This stimulator was used extensively by our team as a hardware platform to develop custom-made neuroprostheses for retraining grasping in individuals with SCI.

FES Therapy for Grasping: Randomized Control Trials

Our team has been working in the area of restoring voluntary grasping function in individuals with stroke and SCI (**Figure 1**) using FES technology for over a decade. The first randomized control trial (RCT) with FET and the first of its kind was conducted by our team in 2006.⁸ The trial was conducted in traumatic, subacute (less than 6 months following SCI) tetraplegic

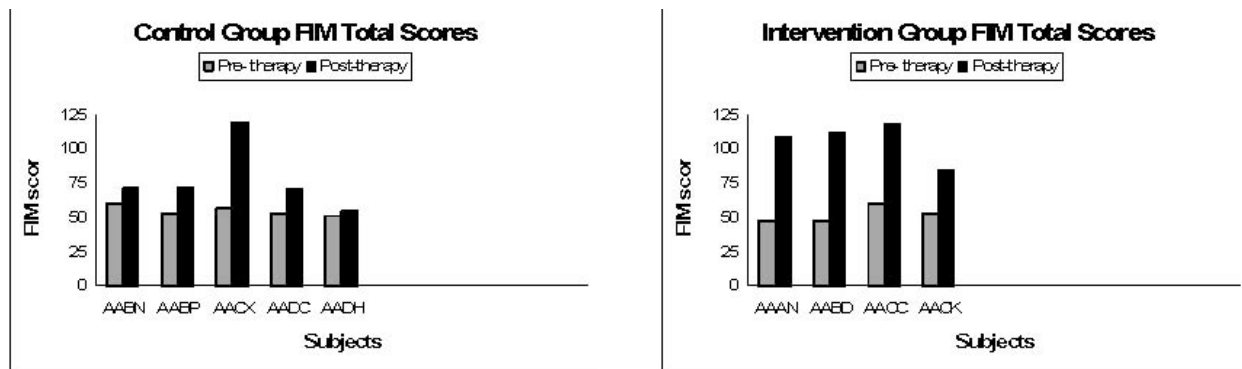


Figure 2. (A) FIM total scores for incomplete SCI for control and intervention group pre and post therapy, respectively (from the study, "Functional electrical therapy: Retraining grasping in spinal cord injury," Popovic et al, 2006).

individuals. In this study, we compared the benefits of conventional occupational therapy alone to conventional occupational therapy plus transcutaneous FET. This was a phase II trial. Participants included both motor complete (ASIA Impairment Scale [AIS] A and B) and incomplete (AIS C and D) SCI individuals. The stimulation parameters used were (1) balanced, biphasic, current regulated electrical pulses; (2) pulse amplitude from 8 to 50 mA (typical values 17-26 mA); (3) pulse width 250 μ s; and (4) pulse frequency from 20 to 70 Hz (typical value 40 Hz). Change in function was recorded using FIM*. The FIM is an 18-item ordinal scale, validated and used within a rehabilitation setting for various patient populations. Individuals who received FET over and above conventional occupational therapy showed considerably better improvements on the FIM (**Figures 2A and 2B**). Another very important and unexpected finding was that individuals with complete SCI appeared to have benefited relatively more from the FET compared to individuals with incomplete SCI. In other words, the relative changes in the outcome measures were higher in individuals with complete SCI compared to individuals with incomplete SCI. For details about protocol and results please refer to Popovic et al.⁸

In 2011, we completed another RCT, this time only in incomplete SCI individuals. Twenty-one participants who were less than 6 months post injury and who qualified based on the study inclusion/exclusion criteria were recruited. Participants were randomized to either control or intervention group, and based on their group allocation they received either 2 hours of conventional occupational therapy or 1 hour of conventional

occupational therapy and 1 hour of FET, respectively. Irrespective of their group allocation, all participants received 40 hours of therapy over and above their routine occupational therapy. The primary outcome measure used to record changes pre and post therapy was the FIM. The secondary outcome measures were the Spinal Cord Independence Measure (SCIM) and the Toronto Rehabilitation Institute Hand Function Test (TRI-HFT).⁹ SCIM is a disability scale that has been specifically developed to evaluate the degree of disability in patients with traumatic and non-traumatic SCI. The TRI-HFT was developed to evaluate improvements in gross motor function of unilateral grasp resulting from FET used to retrain reaching and grasping.⁹ The results of this study were overwhelmingly positive as measured by all 3 outcome measures. The data for the FIM total scores pre and post therapy are shown in **Figure 3**. The participants who received FET not only showed significantly greater improvements over their controls, but also were able to maintain their improvement or continued to improve when followed at 6 months from start of therapy (ie, 4 months post completion of the therapy). The detailed results of the short-term and long-term improvements can be found elsewhere.^{9,13}

Discussion

In all of the above RCTs, our treatment protocol stresses the importance of applying a surface FET intervention that can be tailored and adjusted to patients' needs on a daily basis and can evolve as the patients improve their function. Furthermore, our findings suggest that if a participant who attempts to execute a grasping task is assisted with the FET to carry out that task, he/she is effectively voluntarily generating the motor command

*FIM™ is a trademark of Uniform Data System for Medical Rehabilitation, a division of UB Foundation Activities, Inc.

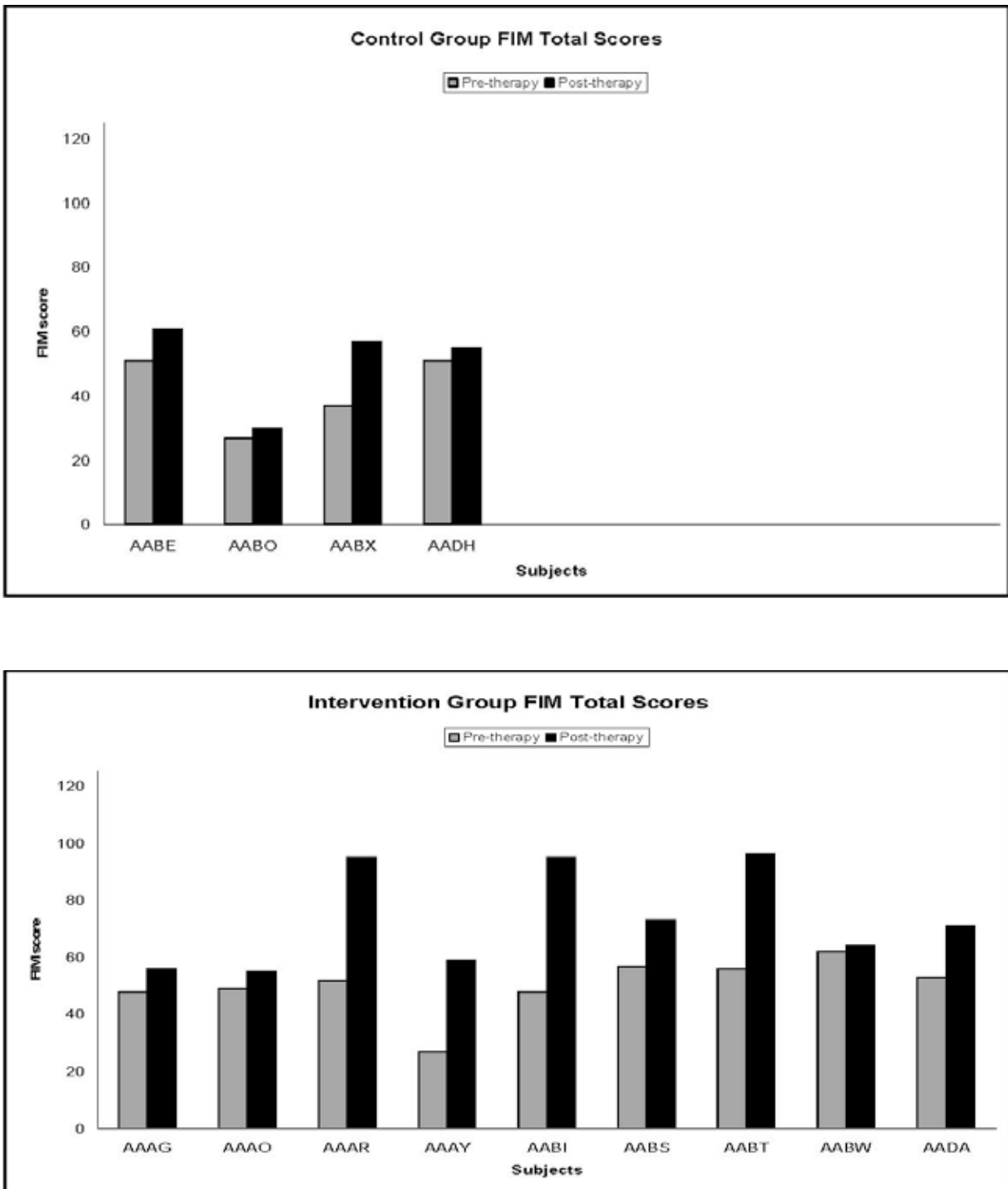


Figure 2. (B) FIM total scores for complete SCI for control and intervention group pre and post therapy, respectively (from the study, "Functional electrical therapy: Retraining grasping in spinal cord injury," Popovic et al., 2006).

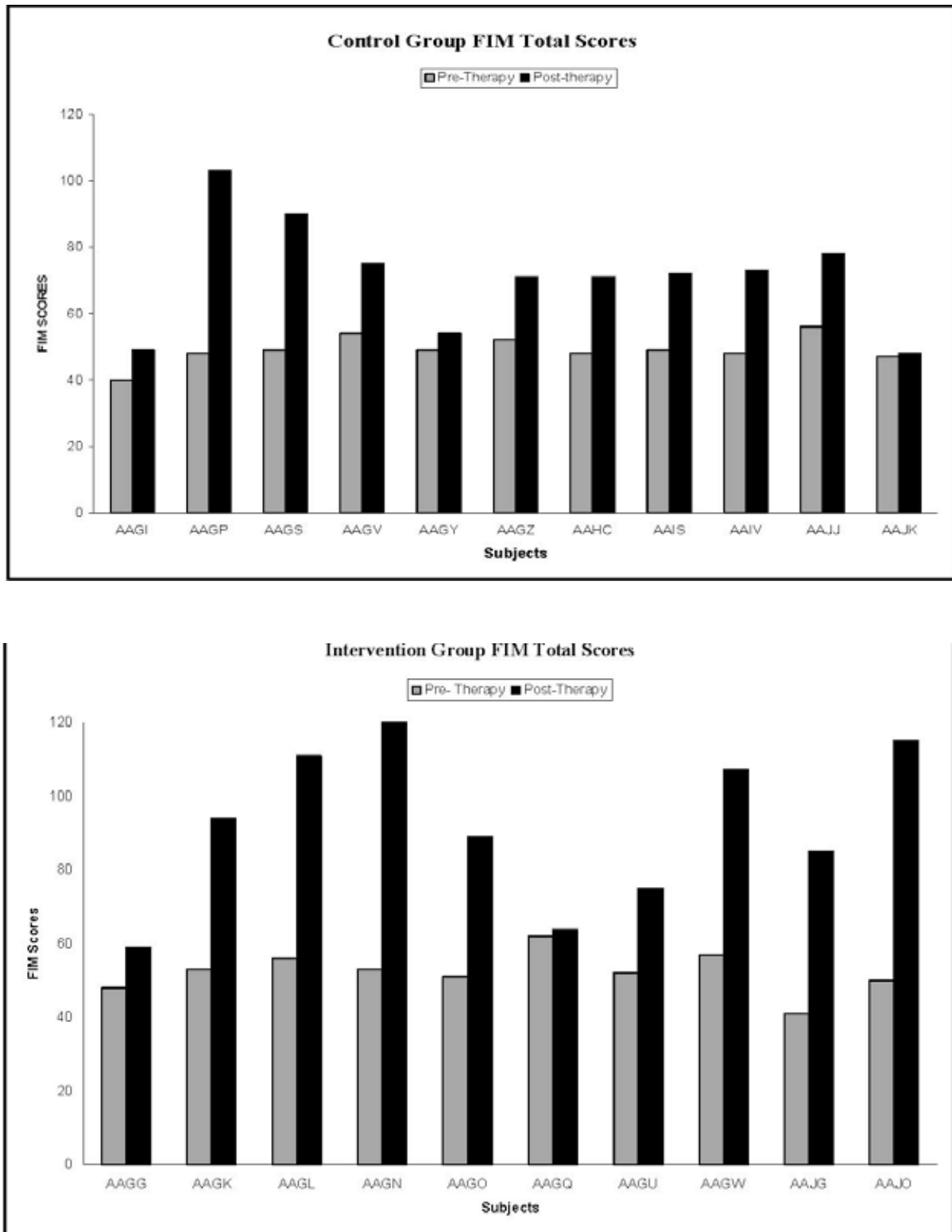


Figure 3. FIM total scores for the control and intervention group pre and post therapy, respectively (from the study, "Functional electrical stimulation therapy of voluntary grasping versus only conventional rehabilitation for patients with subacute incomplete tetraplegia: a randomized clinical trial," Popovic et al, 2011).

(desire to move the arm, that is, *command input*). It is suggested that FET is providing the afferent feedbacks (*system's output*), indicating that the command was executed successfully. We hypothesize that by providing both the command input and system's output to the central nervous system (CNS) repetitively for prolonged periods of time, this type of treatment facilitates functional reorganization and retraining of intact parts of the CNS and allows them to take over the function of the damaged part of the CNS.⁹ It is important to add that during the intervention the participants were performing grasping tasks repetitively. We believe that diversity of meaningful tasks combined with high repetition may play an important role in retraining grasping functions.

Conclusion

On the basis of the aforementioned results, we strongly believe that in the early stage of rehabilitation flexible FES system should be used as an adjunct

therapy along with conventional occupational and physiotherapy regimes to restore or improve voluntary grasping function in individuals post SCI. The characteristics of the FES such as ease of application, flexibility, and adaptability based on individual patient requirements makes it even more desirable. In our experience, this therapy can be effortlessly incorporated within the participant's routine occupational therapy sessions and requires less than 30 minutes to train on part of the occupational therapists.

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REFERENCES

1. Liberson WT, Holmquest HJ, Scot D, Dow M. Functional electrotherapy: stimulation of the peroneal nerve synchronized with the swing phase of the gait of hemiplegic patients. *Arch Phys Med Rehabil.* 1961;42:101-105.
2. Popovic MR, Thrasher TA. Neuroprostheses. In: Wnek GE, Bowlin GL, eds. *Encyclopedia of Biomaterials and Biomedical Engineering*. Vol. 2. New York: Marcel Dekker; 2004:1056-1065.
3. Anderson KD. Targeting recovery: priorities of the spinal cord-injured population. *J Neurotrauma.* 2004;21(10):1371-1383.
4. Peckham PH. Functional electrical stimulation: current status and future prospects of application to the neuromuscular system in spinal cord injury. *Paraplegia.* 1987;24:279-288.
5. Popovic MR, Keller T, Pappas IPI, Dietz V, Morari M. Surface stimulation technology for grasping and walking neuroprostheses. *IEEE Eng Med Biol Mag.* 2001;20:82-93.
6. Prochazka A, Gauthier M, Wieler M, Kanwell Z. The bionic glove: an electrical stimulator garment that provides controlled grasp and hand opening in quadriplegia. *Arch Phys Med Rehabil.* 1997;78:608-614.
7. Popovic MR, Popovic DB, Keller T. Neuroprostheses for grasping. *Neurol Res.* 2002;24:443-452.
8. Popovic MR, Thrasher TA, Adams EM, Takes V, Zivanovic V, Tonack IM. Functional electrical therapy: retraining grasping in spinal cord injury. *Spinal Cord.* 2006;44(3):143-151.
9. Popovic MR, Kapadia N, Zivanovic V, Furlan JC, Craven BC, McGillivray C. Functional electrical stimulation therapy of voluntary grasping versus only conventional rehabilitation for patients with subacute incomplete tetraplegia: a randomized clinical trial [published online ahead of print February 8, 2011]. *Neurorehabil Neural Repair.*
10. Smith B, Peckham PH, Keith M, Roscoe D. An externally powered, multichannel, implantable stimulator for versatile control of paralyzed muscle. *IEEE Trans Biomech Eng.* 1987;34(7):499-508.
11. Napier JR. The prehensile movements of the human hand. *J Bone Joint Surg.* 1956;38B(4): 902-913.
12. IJzerman M, Stoffers T, 't Groen F, Klatte M, Snoek G, Vorsteveld J, Nathan R, Hermens H. The NESS handmaster orthosis: restoration of hand function in C5 and stroke patients by means of electrical stimulation. *J Rehabil Sci.* 1996;9(3):86-89.
13. Kapadia N, Zivanovic V, Furlan J, Craven BC, McGillivray C, Popovic MR. Toronto Rehabilitation Institute's functional electrical stimulation therapy for grasping in traumatic incomplete spinal cord injury: randomized control trial. *Artif Organs.* 2011;35(3):212-6. doi: 10.1111/j.1525-1594.2011.01216.x.
14. Popovic D, Stojanovic A, Pjanovic A, Radosavljevic S, Popovic M, Jovic S, Vulvovic D. Clinical evaluation of the bionic glove. *Arch Phys Med Rehabil.* 1999;80(3):299-304.
15. Popovic MR, Keller T, Pappas IPI, Dietz V, Morari M. Surface stimulation technology for grasping and walking neuroprostheses. *IEEE Eng Med Biol Mag.* 2001;20:82-93.
16. Popovic MB, Popovic DB. Cloning biological synergies improves control of elbow neuro-prosthesis. *IEEE Eng Med Biol Mag.* 2001;24(1):74-81.
17. Popovic MR, Keller T. Modular transcutaneous

- functional electrical stimulation system. *Med Eng Physics*. 2005;27(1):81-92.
18. Pappas IPI, Popovic MR, Keller T, Dietz V, Morari M. A reliable gait phase detection system. *IEEE Trans Neural Syst Rehabil Eng*. 2001;9(2):113-125.
19. Márquez-Chin C, Popovic MR, Cameron T, Lozano AM, Chen R, Control of a neuroprosthesis for grasping using offline classification of electrocorticographic signals: Case study. *Spinal Cord*. 2009;47:802-808.