Functional Electrical Theraphy (FET) for the Training of Gait in Patients with Hemiplegia

Functional Electrical Theraphy (FET) for the Training of Gait in Patients with Hemiplegia

Functional and Physiological Assessments

PhD Thesis by

Jovana Kojović

Center for Sensory-Motor Interaction (SMI),
Department of Health Science and Technology,
Aalborg University, Aalborg, Denmark

River Publishers
Aalborg

ISBN 978-87-92982-16-2 (e-book)

Published, sold and distributed by:
River Publishers
P.O. Box 1657
Algade 42
9000 Aalborg
Denmark

Tel.: +45369953197
www.riverpublishers.com

Table of contents

Chapter 1

Chapter 2 *Sensor-Driven Four-Channel Stimulation of Paretic Leg: Functional Electrical Walking Therapy*

Chapter 3 *Recovery of motor function after stroke: a polymyography-based analysis*

Summary

Gait recovery is a major objective in the rehabilitation program for stroke patients. Therefore, for many decades, hemiplegic gait has been the object of study for the development of methods for gait analysis and rehabilitation.

In this thesis we introduced new therapeutic method in gait rehabilitation, based on application of sensors driven functional electrical stimulation. The automatic control relates to the timing of stimulation of four muscles. The sensor system comprises accelerometers and force-sensing resistors. The automatic control implements IF-THEN rules designed by mapping of sensors and muscle activation patterns. The evaluation included 13 stroke patients assigned to a FET group or a control (CON) group. Both groups were treated with a standard rehabilitation program and 45 minutes of walking for 5 days over the course of 4 weeks. The difference between the groups was that the FET group received electrical stimulation during walking. The Fugl-Meyer (FM) test for the lower extremities, Barthel Index (BI), walking velocity over a 6-meter distance, and Physiological Cost Index (PCI) were assessed at the beginning and at the end of the treatment. Subjects within the FET and CON groups had comparable baseline outcome measures. In the FET group, we determined significant differences in the mean values of all tested parameters ($p < 0.05$). In the CON group we found significant differences in FM test scores and BI ($p < 0.05$), but the differences in walking velocity and PCI were not significant ($p > 0.05$). We also found a larger increase in mean values of outcome measures in the FET group compared with the CON group (e.g., average velocity increased 60% in the FET group compared to an 11% increase in the CON group). We also present a method for assessing muscle activation patterns during goal-directed movement in a cohort study from a randomized clinical trial ,that followed the recovery of motor function during and after intensive gait training, assisted by sensor-driven, four-channel electrical stimulation. The instrument that we developed allows for the simultaneous recordings of up to 16 channels that are wirelessly sent to a host computer, which then provides feedback to the subject. The inputs connectors to the portable instrument are electromyography (EMG) amplifiers, and include inertial and other sensors. We show that this method is sensitive enough
to show changes in muscle activation patterns in stroke patients before and after gait training(four weeks, five days a week, 30 minutes daily). We also show that the recovery decreases the differences between patterns of muscle activities (e.g., levels of muscle activations and median frequencies) assessed in hemiplegic and healthy subjects. This method allows for the analysis of muscle contributions and activation patterns; therefore, it might be possible to better understand the physiology behind the recovery of function. This EMG analysis provides a quantification of recovery that is a valuable addition to other measures, such as the Fugl-Meyer score, the Berg-Balance score, gait speed, and the symmetry index.

Danish Summary / Dansk sammenfatning

Gangart opsving er et vigtigt mål i det rehabiliteringsprogram for patienter med slagtilfælde. Derfor, i mange årtier har hemiplegisk gangart været genstand for undersøgelse af udviklingen af metoder til ganganalyse og rehabilitering.

I denne afhandling har vi indført nye terapeutic metode i gangart rehabilitering, baseret på anvendelse af sensorer drevet funktionel elektrisk stimulation. Den automatiske styring vedrører timingen af stimulering af fire muskler. Sensoren Systemet består af accelerometre og trykfølsomme modstande. Den automatiske styring implementerer If-Then regler, designet af kortlægning af sensorer og muskel aktivering mønstre. Evalueringen omfattede 13 patienter med slagtilfælde er tildelt en FET gruppe eller en kontrol (CON) gruppe. Begge grupper blev behandlet med et standard rehabiliteringsprogram og 45 minutter til fods i 5 dage i løbet af 4 uger. Forskellen mellem grupperne var, at FET gruppe fik elektrisk stimulation under gang. Den Fugl-Meyer (FM) test for den nedre ekstremiteter blev Barthel Index (BI), gå hastighed over en 6-

meters afstand, og fysiologiske Cost Index (PCI) vurderede i begyndelsen og ved slutningen af behandlingen.

Emner inden for FET og CON grupper var sammenlignelige ved baseline resultatmål. I FET-gruppen, fastlægges vi betydelige forskelle i de gennemsnitlige værdier for alle testede parametre (p <0,05). I CON gruppen fandt vi signifikante forskelle i FM prøveresultater og BI (p <0,05), men forskellene i gå-hastighed og PCI var ikke signifikant (p> 0,05). Vi har også fundet en større stigning i den gennemsnitlige værdier af effektmål i FET-gruppen sammenlignet med CON-gruppen (fx gennemsnitlig hastighed steg 60% i FET- gruppen sammenlignet med en 11% stigning i CON-gruppen). Vi præsenterer også en metode til vurdering af muskel aktivering mønstre i løbet af målrettet bevægelse i en kohorte undersøgelse fra et randomiseret klinisk forsøg, der fulgte inddrivelse af motorisk funktion under og efter en intensiv gang træning, bistået af sensor-drevet, fire-kanals elektrisk stimulation . Det instrument, som vi udviklede giver mulighed for samtidige optagelser af op til 16 kanaler, der er trådløst sendes til en værtscomputer, som derefter giver feedback til emnet. Indgangene stik til den

bærbare instrumentet elektromyografi (EMG) forstærkere, og omfatter inerti og andre sensorer. Vi viser, at denne metode er følsom nok
at vise ændringer i muskel aktivering mønstre hos patienter med slagtilfælde før og efter gangart uddannelse (fire uger, fem dage om ugen, 30 minutter dagligt). Vi viser også, at opsvinget reducerer forskellene mellem mønstre af muskel-aktiviteter (f.eks niveauer af muskel aktiveringer og median frekvenser) vurderes i hemiplegisk og raske personer. Denne metode giver mulighed for analyse af muskel-bidrag og aktivering mønstre, og derfor kan det være muligt for bedre at forstå fysiologien bag inddrivelsen af funktion. Denne EMG analyse giver en kvantificering af nyttiggørelse, der er et værdifuldt supplement til andre foranstaltninger, såsom Fugl-Meyer score, Berg-Balance score, gangart hastighed, og symmetrien indekset.

Acknowledgements

I would like to thank all people who contributed and supported this project and ones who made this journey meaningful.

First of all, I am thankful to my supervisor Prof. Dejan B.Popović, for giving me a chance and believing that I can make it. Thanks for the guidance, sharing knowledge, encouraging, and most of all patience to make the thesis complete.

A special appreciation goes to all patients from the clinics that had understanding and will to participate and help our research.

I wish to thank all the staff at the Center for Sensory Motor Interaction(SMI), University of Aalborg and staff from the Institute for Neurorehabilitation"Dr.Miroslav Zotovic",Belgrade, Serbia and Clinic for Rehabilitation,Nis.

I am very grateful to all my co-authors, Nadica Miljković, Strahinja Došen, Milica Jovicić, Milica Janković and Prof. Mirjana B. Popović for their valuable professional help and very good spirit they brought.

A special words of thanks to all my dear friends and all the colleagues that made my staying in Denmark as one of the best experience in my life.

At the end, I can not find the right words to express my gratitude to my parents and family for all their love and support.

List of Abbreviations

ACC-Accelerometer
BB-Berg Balance score
BI- Barthel Index
BF-Biceps Femoris
Ci-Coactivation
CMRR-Common Mode Rejection Ratios
CNS-Central Nervous System
CPG-Central Pattern Generator
CT-Computer Tomography
CVA-Cerebro-vascular accident
EMG-Electromyography
FES-Functional Electrical Stimulation
FET-Functional Electrical Therapy
FM-Fugl Mayer score
fMRI-functional Magnetic Resonance Imaging
FSR-Force-sensing-resistor
HAM-Hamstrings
LG-Lateral Gastrocnemius
MAV-mean absolute value
MNF-mean frequency
MNP-Motor Neural Prosthesis
NIRS-Near Infra Read Spectroscopy
TA-Tibialis Anterior
TMS-Transcranial Magnetic Stimulation
PCI-Physiological Cost Index
PSD-Power Spectral Density
QA-Quadriceps
RBC-Rule Based Control
RF-Rectus Femoris
RMS -root-mean-square
SD-Standard Deviation
SI-Symmetry Index
SOL-Soleus

Chapter 1

Introduction

People affected by the brain stroke are left with many motor and sensory defects. One of the most common consequences is destroyed gait pattern.

Before talking about gait deficits lets define the components of “healthy gait” and their control mechanism.

Walking represents complex motor control task which requires the integration of the central nervous system and its interaction with peripheral sensory systems in controlling the muscles, acting on a skeletal system with many degrees of freedom.

The elementary sequence of walking is termed the gait cycle. It starts when the heel of the ipsilateral leg touches the ground and ends just before the same heel touches the ground again. The heel contact is termed the initial contact; thus the gait cycle is a period between two initial contacts. The gait cycle can be divided into two distinct phases: the stance phase for normal, self paced level walking lasts for 60-65% of the gait cycle, while the swing phase lasts for the remaining 35-40%. (Figure1.)

The period during which both legs have ground contact is called double support phase (DSP) and the period during which only one leg is contacting the ground is called single support phase (SSP). So two DSPs and two SSPs compose one gait cycle.

The first DSP starts simultaneously with the stance phase of the ipsilateral leg and lasts up to the moment when the contralateral leg starts the swing being between 16 to 20 percent of the gait cycle.

Different terminology is applied in defying the subsequence of the gait cycle .The stance phase is sequenced to several sub-phases: heel contact, foot-flat, heel off, and toe off or initial, middle and terminal phase.

We can not use any standards in defining “normal” walking, since there are differences between male and female, different age groups, features and the patterns of walking are different for various environmental conditions, directions off walking and different walking speeds. However, there are still some characteristic from able bodied subjects walking which we use as a measures in gait analyzes.

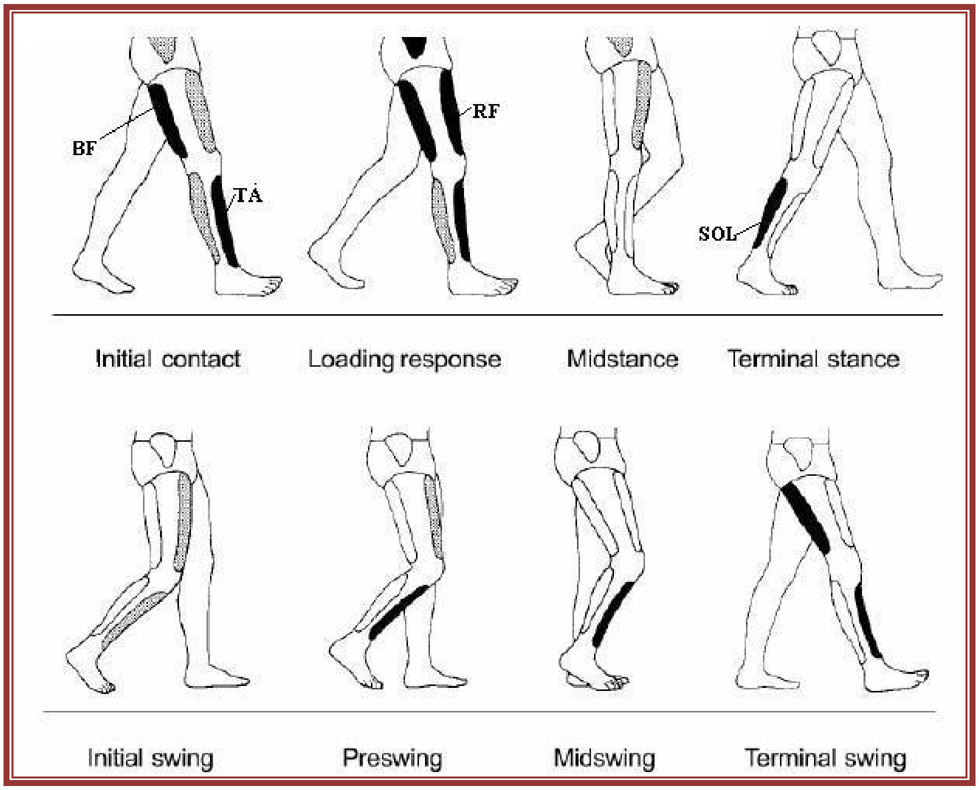


Figure1.Schematic presentation of gait cycle indicating sub phases and activation of the muscles .Adopted from Popovic D.2000

To perform normal walking, there are many conditions to be satisfied. The human mechanical system operates in a gravitational environment with a likely small base of support and center of mass located at a considerable distance from the ground. This makes difficulties in keeping the stable vertical posture, which is first condition to be satisfied. It is important to control the swinging leg to safely move without touching the ground and to provide gentle landing at the ground at the end of the swing.

To regulate such a system a well neural control that defines total limb synergies, and allows enough flexibility to respond to a wide variety of perturbations and with enough adaptability to anticipate changes sufficiently well in advance is necessary.

A various neural substrates take a role in the control of locomotion. Thus, identifying them is important when trying to restore walking of human with disability. The way to test some of hypotheses is from animal experiments. So the findings from the studies can not be always applied to bipedal walking. The most used methods are: spinal, decerebrate, and decorticate preparations.

In the spinal preparation one can study how the spinal cord can produce reasonably complex and normal muscle activation patterns in response to an unpatterned stimulus. The spinal cord can provide appropriate interlimb coordination in addition to the intralimb coordination. It is also able to functionally modulate reflex responses (Forssberg, 1979 a and b) and carry out other stereotypic tasks concurrently (Carter and Smith, 1986a and b).The modulation of reflex responses indicates that the spinal cord produces not only the appropriate patterns for the effector system, but also suitably primes the sensory system so that the reflex responses are compatible with the movement pattern. The ability to carry out other stereotypic tasks concurrently suggests that the spinal cord is not fully used for locomotion.

The cerebellum is essential for the fine coordination of the locomotor patterns by virtue of the afferent information it receives and the influence it has on various descending pathways.

It's been reported that cortical structures play an important role in the skilled locomotor behavior. Amstrong (1988) and Drew (1988).

The demonstration that simple unpatterned input to the spinal cord can produce complex rhythmic activation patterns led to the principle of central pattern generator for the control of locomotion.(Delcomyn,1980,Grillner,1985,Shik and Orlovsky,1976).

A central pattern generator (CPG) is a neuronal network capable of generating a rhythmic pattern of motor activity in the absence of phasic sensory input from peripheral receptors. Although the centrally generated pattern is sometimes very similar to the normal pattern; there are often some significant differences. Sensory information from peripheral receptors and signals from other region of the CNS usually modify the basic pattern produced by a CPG.

The generation of rhythmic motor activity by CPGs depends on three factors: 1. the cellular properties of individual nerve cells within the network 2.the properties of the synaptic junctions between neurons 3. The interconnections between neurons.

Most CPGs produce a complex temporal pattern of activation of different groups of motor neurons. Sometimes that can be divided into a number of distinct phases. The sequencing of motor pattern is regulated by a number of mechanisms. The simplest mechanism is mutual inhibition; interneurons fire out of phase with each other, in most cases reciprocal due to their inhibitory connections.

A number of recent studies have used this approach to explore the bases of central motor programming by decomposing muscle activation patterns as a means to look backward from the periphery to the CNS (Davis and Vaughan 1993; d'Avella and others 2003; Hart and Giszter 2004; Ivanenko and others 2004). Spinal pattern generators for locomotion have now been studied in several mammals (Orlovsky and others 1999). And **it** has also been suggested that MNs themselves may be integral elements of CPGs (Marder 1991; O'Donovan and others 1998).

However, the details of such circuitry in the human spinal cord are still largely unknown (Winter 1989; Duysens and Van de Crommert 1998; Lacquaniti and others 1999; Edgerton and others 2001; Capaday 2002; Ivanenko and others 2003; Dietz and Colombo 2004; Grasso and others 2004).

Maps constructed from data recorded during treadmill locomotion at several different speeds show a number of common features (Ivanenko, Poppele, and others 2006). One is that MN activity tends to occur in bursts that are temporally aligned across several spinal segments. For each spinal segment, there are generally two activity bursts occurring in each locomotion cycle corresponding to one burst during the stance phase and the other during swing (Fig. 2). These maps are relatively invariant across subjects, especially at high walking speeds (Ivanenko, Poppele, and others 2006), despite the fact that the root innervation of many muscles does show interindividual variations.

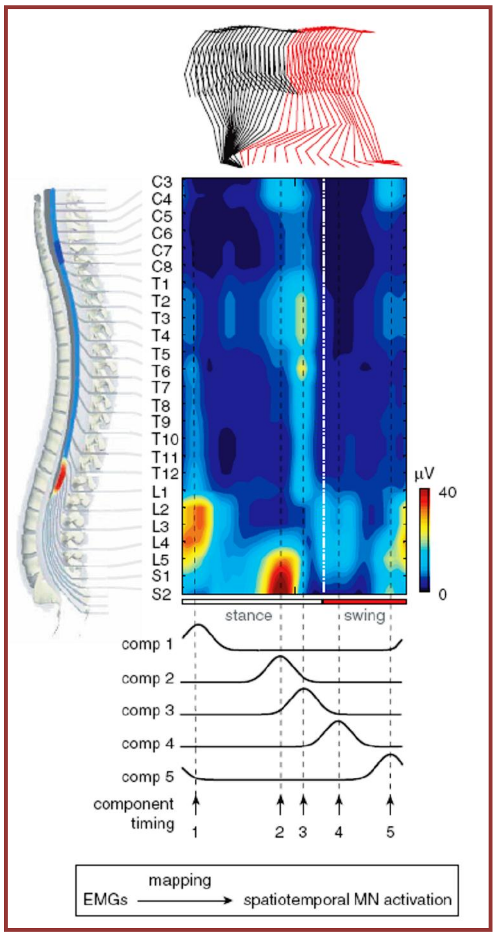


Figure. 2. Spatiotemporal patterns of ipsilateral (α–motoneuronMN) activity along the rostrocaudal axis of the spinal cord during walking on a treadmill at 5 km/h. Pattern is plotted versus normalized gait cycle. Output pattern was constructed by mapping the recorded electromyographic (EMG) waveform of 32 ipsilateral limb and trunk and shoulder muscles (non normalized method, adapted from Ivanenko, Poppele, and others [2006].

Five Gaussian activation components that correspond to five major discrete periods of activity and account for ~90% of total variance are shown on the bottom.

GAIT REHABILITATION THERAPIES AND STROKE

A stroke, known medically as a cerebrovascular accident (CVA) is the rapidly developing loss of brain functions due to the disturbances in the blood supply to the brain. Stroke can be due to the ischemia (lack of the blood flow), caused by blockage (thrombosis, arterial embolism), or a hemorrhage (leakage of blood).As a result, the affected area of the brain is unable to function, which might result in an inability to move one or more limbs on one side of the body, inability to understand or formulate speech, or an inability to see one side of the visual field.

An ischemic stroke is occasionally treated in a hospital with thrombolysis (also known as a "clot buster"), and some hemorrhagic strokes benefit from neurosurgery. Treatment to recover any lost function is termed stroke rehabilitation, ideally in a stroke unit and involving health professions such as speech and language therapy, physical therapy and occupational therapy.

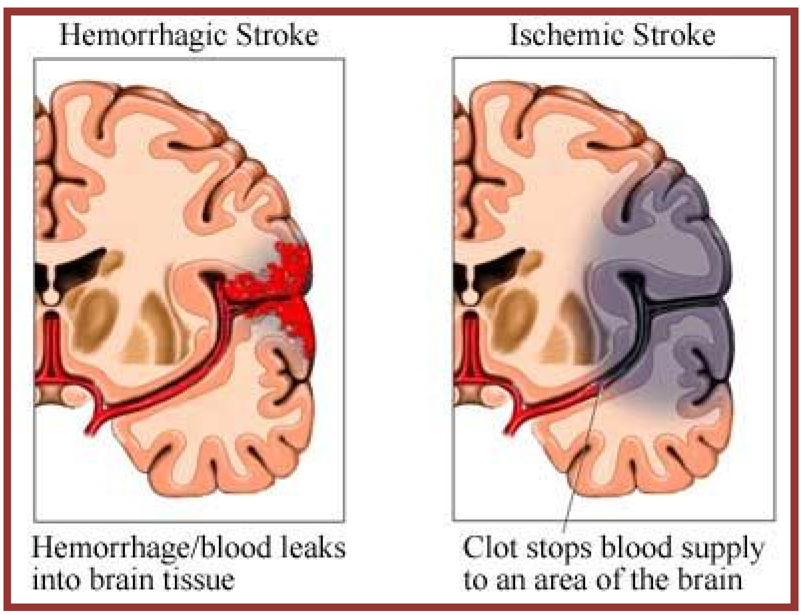


Figure 3.Hemorrhagic vs. Ischemic Stroke. Adopted from Nucleus Medical Media, Inc

Despite undergoing rehabilitation many people are left with a walking deficit after stroke. Gait deficits include: inadequate pelvic, knee and ankle control during loading, mid stance and terminal stance; inadequate hip, knee and ankle flexion excursion through mid-swing; inadequate knee extension, hip flexion and ankle dorsiflexion, excursion in terminal swing, and abnormal timing among hip, knee and ankle joint movements. Motor weakness, poor motor control and spasticity result in altered gait patter (walking), poor balance, risk of falls, and increased energy expenditure during walking. Ineffective ankle dorsiflexion during swing (drop-foot) and failure to achieve heel strike at initial contact are common problems that disturb gait pattern after stroke. So in such patients the relearning of gait is difficult and long lasting [Bohannon et al.1991].

Despite of many years of application of physical therapy to improve the condition of stroke patients there are still many unknowns and paradoxes. Up to date there is no scientific evidence about which one is the best treatment (Kollen et al. 2009, Burke et al 2008).

GAIT RESTORATION TECHNIQUES

Modern concepts of motor learning, favor a task specific repetitive training .Repetitive execution of identical or similar movements of the limb has been identified as crucial for motor learning and recovery in stroke subjects i.e." who wants to regain walking, has to walk". [Kwakkel et al. 2004].

Robotic devices:

Robotic devices have currently become widely accepted among many researchers and clinicians and are being used in rehabilitation of physical impairments in both the upper and lower limbs.

These devices provide safe and intensive rehabilitation to people with mild to severe motor impairments after neurologic injury. Besides, kinematic and kinetic data can be obtained throughout therapy sessions or during a separate evaluation in order to control and quantify the intensity of practice, measure changes and assess motor impairments such as spasticity, tone or strength with better sensitivity and reliability than standard clinical scales.

Task-specific repetitive movements can improve muscular strength, movement coordination and locomotor retraining in neurological impaired patient. In addition, this approach reduces the amount of physical assistance required to walk (more than one therapist is necessary to provide a therapeutic intervention); therefore robotic devices may also help reduce health care costs).

The most common robotic devices for gait restoration are based on task-specific repetitive movements. They have been designed as simple electromechanical aids for walking, such as the treadmill with body weight support (BWS) (McCain et al. 2008), as end-effectors, such as the Gait Trainer (Reha-Technologies, Germany, GT) (Hesse et al., 2000), or as electromechanical exoskeletons, such as the Lokomat (Hocoma, AG;

Switzerland) (Colombo, 2000). On treadmills, only the percentage of body weight support and walking speed can be selected, whereas on the Lokomat, the rehabilitation team can even decide the proper joint kinematics of the patients' lower limbs. End effector devices lie between these two extremes, including a system for body weight support and a controller of end-point (feet) trajectories.

A fundamental aspect of these device is hence the presence of an electromechanical system for the body weight support that permits a greater number of steps within a training session than conventional therapy, in which body weight is manually supported by one or two therapists and/or a walker (Moseley et al. 2003; Pohl et al. 2007).

This technique consists on using a suspension system with a harness to provide a symmetrical removal of a percentage of the patient's body weight as he/she walks on a treadmill or while the device moves or support the patient to move his/her lower limbs. This alternative facilitates walking in patients with neurological injuries who are normally unable to cope with bearing full weight and is usually used in stroke rehabilitation. This method allows the beginning of gait training in early stages of the rehabilitation process. The effectiveness of treadmill training with individuals post-stroke has been analyzed by many researchers. Several studies support that retraining gait with BWS leads to a more successful recovery of ambulation with respect to over ground walking speed and endurance, functional balance, lower-limb motor recovery and other important gait characteristics such as symmetry, stride length and double stance time.

Visintin et al .(1998) reported that treadmill therapy with BWS was more effective than without BWS in subacute, nonambulatory stroke patients, and treadmill therapy also showed advantages over conventional gait training with respect to cardiovascular fitness and walking ability.

Luft et al. (2008) compared the effects of 6-month treadmill training versus comparable duration stretching on walking, aerobic fitness and in a subset on brain activation measured by functional MRI. The outcomes of this randomized controlled trial (RCT) suggested that treadmill training promotes gait recovery and fitness, and provided evidence of neuroplastic mechanisms.

Mayr et al.,(2007) found more improvement during the Lokomat training phase than during the conventional physical therapy phase after a rehabilitation program that applied these two different techniques for gait training).

On the other hand, Peshkin et al .(2005) attempted to identify users and therapists' needs through observations and interviews in rehabilitation settings in order to develop a new robotic device for gait retraining in over-ground contexts. Therefore they intended to establish key tasks and assess the kinematics required to support those tasks with the robotic device making the system able to engage intense,

locomotor-specific, BWS training over ground while performing functional tasks.
As most complex robots need to be permanently installed in a room, patients have to be moved from their beds to attend the rehabilitation. This is the main reason why therapy cannot be provided as soon as possible after stroke. In order to overcome this limitation, a robotic platform was developed by Monaco et al. (2008) that consist of providing leg manipulation, with joint trajectories comparable with those related to natural walking for bedridden patients).
However, other studies have provided conflicting results regarding the effectiveness of robotic devices for ambulatory and/or chronic patients with stroke were also found (Hornby et al. 2008; Hidler et al. 2009). A recently updated Cochrane review has demonstrated that the use of electromechanical devices for gait rehabilitation increases the likelihood of walking independently in patients with subacute stroke (odd ratio = 2.56) but not in patients with chronic stroke (odd ratio = 0.63) (Mehrlhoz et al. 2007). Furthermore, some other problems are still limiting a wider diffusion of robotic devices for gait restoring, such as their high costs and the skepticism of some members of rehabilitation teams (Dobkin 2004) probably based on the lacks of clear guidelines about robotic training protocols tailored on patients’ motor capacity.
More recently, Morone and colleagues have proposed to change the scientific question about the effectiveness of these robotic devices into “who may benefit from robotic-assisted gait training?” [Morone et al., 2011]. The authors found that robotic therapy combined with conventional therapy is more effective than conventional therapy alone in severely affected patients.
The movement of the lower limbs during locomotion is rather stereotypical, at least in the sagittal plane and is thus suitable for machine support. The weight of the patients and the necessary acceleration of body mass, for example during push-off, pose the major problems. Hesse and co-workers presented the electromechanical gait trainer, GT I, aimed at relief of the strenuous effort of therapists during locomotor therapy on the treadmill when setting the paretic limbs .The harness-secured patient was positioned on two foot-plates, whose movements simulated the stance and swing phase in a physiological manner. Step length and cadence could be set individually, and ropes attached to the harness controlled the movement of the centre of mass in the vertical and horizontal direction in a phase-dependent manner. Functional electrical stimulation of the thigh muscles during the stance phase assisted knee extension during the stance phase. Gait analysis showed that sagittal joint kinematics and the muscle activation pattern of various lower limb muscles of hemiparetic patients corresponded to each other on the gait trainer and on the treadmill.On the machine, patients walked more symmetrically, with less spasticity, and the vertical centre of mass displacement was more physiological.

A first baseline treatment study included 12 chronic non-ambulatory hemiparetic patients (46 months postictum).Four weeks of additional daily therapy at 20 min on the machine resulted in a marked improvement of gait ability and muscle activation compared with the preceding 3-week baseline of conventional therapy. During a single 20-min session, the patients practiced 800–1000 steps. Next, a randomized cross-over study included 30 non ambulatory subacute hemiparetic patients randomly allocated to two groups, A and B, who either followed an A–B–A (group A) or an B–A–B design (group B) with an equals 2 weeks gait trainer and B equals 2 weeks treadmill. One instead of two therapists was required on the machine. Gait ability improved steadily in both groups, with patients in group A walking significantly better (i.e. more independently) during the last phase. Gait velocity did not differ between the groups. At follow-up the effects had waned.

Colombo and co-workers combined a treadmill with a driven gait orthosis (Lokomat) for the locomotor treatment of spinal cord-injured (SCI) patients. The adjustable exoskeleton included position-controlled actuators at the knee and hip joints to secure the swing phase, while the treadmill provided the stance phase.

The ankles were set passively. The exoskeleton was fixed to the railing of the treadmill by a rotatable parallelogram. This set-up allowed the upward and downward movement of the body and the sagittal movements of the lower limb joints. SCI patients could tolerate the automated training for up to 60 min, whereas the manually assisted therapy on the treadmill only lasted 10–15 min. Among the lower limb devices, the Lokomat has not yet been tested. For the electromechanical gait trainer, GT I, one cross-over study, conducted by the group also responsible for its design, positively evaluated the machine compared with treadmill training with BWS. There is no evidence on any multi-centre studies. Technical challenges are the implementation of force control (to lessen the opponents' major argument of a purely passive therapy) and the possibility of practicing an individualized instead of a stereotypical gait pattern. The future will surely see machines for the repetitive practice not only of floor walking but also of stair climbing up and down, and the simulation of sudden perturbations.

The machines are intended to be an adjunctive tool to increase the intensity of therapy in line with modern principles of motor rehabilitation. But a robot can never replace the multi-level interaction between patients and therapists.

Popovic and Veg, introduced mobile walking balance support of walking. The Walkaround® is a mobile walking assist that supports a compromised posture and contributes to safer walking. The basic elements of the Walkaround® are a special lumbar belt and adjustable suspension system with springs that connect the

lumbar belt to the rigid tripod with wheels. The idea behind the design follows biomechanical studies presented by (Matjačić et al.,2000 *)* which suggested that for control of balance under minor perturbations in the sagittal plane it is important to control stiffness at the ankle joints, and for perturbations in the frontal plane it is important to control the stiffness in the hip joints. The suspension system within the Walkaround® provides this required controlled stiffness of the body with respect to the rigid frame. In addition, the suspension system and the lumbar belt provide safety against falls and subsequent injury.
The design of the Walkaround® allows for the device to be combined with Functional Electrical Stimulation or other orthotic systems to assist leg movements and support.
The differences in walking parameters that were measured in individuals with no known motor deficiencies were small, suggesting that the Walkaround introduced only small constraints.
The walking assisted by the Walkaround®, when compared to walking without the Walkaround®, showed significant improvement as assessed by walking speed and the index of symmetry in acute hemiplegic individuals.

Functional Electrical Stimulation

Among other techniques for restoration of motor functions and improvement of gait recovery in individuals with hemiplegia, motor neural prosthesis (MNP) has been suggested. MNP is the system that uses functional electrical stimulation (FES) to activate paralyzed muscle in precise sequence and magnitude so as to directly accomplish functional task. FES is a treatment that can provide critical practice of close to normal movements by electrically inducing muscle contractions and coordinated movements not possible volitionally. Physiological effects that have been described to FES include muscle strengthening, inhibition of antagonist spasticity, correction of contractures, and increased passive range of motion and facilitation of voluntary motor control. The mechanisms responsible for improvement are uncertain but may involve increased presynaptic inhibition of muscle spindle reflex activity. [Glanz M ET al.1996]
The initial application of neuroprostheses in hemiplegics focused on transcutaneous peroneal nerve stimulation to treat ankle dorsiflexion weakness has been described by Liberson et al in 1961.
After his introduction, the development of many devises, which were based on this principle, was started: e.g. Functional electronic peroneal brace FEPB. The Odstock Foot-drop Stimulator (ODFS).The single channel foot-drop stimulator, Walk Aid etc. Besides the stimulators with surface electrodes, the implanted peroneal stimulator were developed (Medtronic INC.) ActiGait and Finetech Dropped Foot System are contemporary implantable devices.

Soon after the use of single channel for functional electrical stimulators for foot-droop prevention, researchers showed a tendency to selectively stimulate the muscles for dorsiflexion of the foot as well as the other main muscle groups in a paralyzed leg. (Vodovnik et al).This started a period of development of different multichannel stimulators and study of control principles, stimulation sequences, correction of gait anomalies, and therapeutic effects of multichannel functional electrical stimulation. The main advantage of this system is the plausibility to activate many different muscle groups. Pioneering work in multichannel FES with surface electrodes was done by research group from Ljubljana (Slovenia): First, they developed a three-channel system for assisting the swing phase, and later three more channels were added with the aim to stimulate all three joints of the paretic leg during both stance and swing phase in individuals with hemiplegia. The examples of similar system are Vienna FES system, Complex Motion and UNA FET system. Although they are different in technology they are based on simple open-loop control, thus stimulation is triggered by hand switch or gait sensors. That way only basic gaits events could be detect.

Over the last 30 years, various approaches using multi channel functional electrical stimulation in the rehabilitation of gait in CVA patients have been investigated. Modern concepts of motor learning, favor a task specific repetitive training .The approach of repetitive execution of identical or similar movements of the limb has been identified as crucial for motor learning and recovery in stroke subjects i.e." who wants to regain walking, has to walk".

In the 1990s, FES has been increasingly used to treat the lower extremity of stroke subjects. Bogataj et al. compared 2 groups of stroke survivors receiving 3 weeks of FES, preceded or followed by 3 weeks of conventional therapy. Treatment was given 5 days per week for 7 to 21 days. The results showed that more subjects were able to walk and lived independently after FES.It has been suggested that intensive exercise combined with therapeutic multi-channels functional electrical stimulation is a valuable neurorehabilitation method which promoted recovery and leads to carry-over effects. This treatment was termed Functional Electrical Therapy (FET).

One of the recent approach in neurorehabilitation is the application of electrical stimulation under the sole of the foot .It has been reported that reflexed based support induced by electrical stimulation can facilitate gait. Applying electrical stimulation on the different part of the sole of the foot cutaneous input is sent to the spinal cord.It artificially activates muscles of the lower leg through withdrawal reflex pathways. During withdrawal, the contraction of muscles is performed in a coordinated fashion in order to move the stimulated limb away from the painful stimuli while maintaining the balance [Andersen et al.2003, Spaich et al. 2005, Emborg et al.2009].

- The most of the studies demonstrated the advantage of combined multi channel stimulation and standard rehabilitation, but the intervals of intervention, as the stage of the stroke were varied.

We decided to implement sensor system in FES and to test it in patients after acute stage of stroke, which showed initial improvements in their walking ability, meaning the ability to walk with the assistance of therapists.

References:

Barbeau H, Visintin M. Optimal outcomes obtained with body-weight support combined with treadmill training in stroke subjects. Arch Phys Med Rehabil 2003 (Oct.); 84(10):1458 –65.

Bogataj U, Gros N, Kljajic M, Acimovic-Janezic R. Enhanced rehabilitation of gait after stroke: a case report of a therapeutic approach using multichannel functional electrical stimulation. IEEE trans. rehabil. eng., June 1997, 5, no. 2, pp. 221-232

Bogataj U, Gros N, Kljajic M, Acimovic-Janezic R, Malezic M. The rehabilitation of gait in patients with hemiplegia: a comparison between conventional therapy and multichannel functional electrical stimulation therapy. Phys. therapy, June 1995, 75, no. 6, pp. 490-502

Buurke J.H., Nene B.H, Kwakkel G, Erren WoltersV., IjzermanM.J and Hermens H."Recovery of Gait after Stroke: What Changes? Neurorehabil Neural Repair, 22,676-683, 2008

Colombo G. The "Lokomat" a driven ambulatory orthosis. Med Orth Tech. 2000; 6: 178-181.

Dally JJ and Ruff" Construction of efficacious gait and upper limb functional interventions based on brain plasticity evidence and model based measures for stroke patients". The scientific World Journal, 7, 20312045

Daly JJ, Barnickle K, Kobetic R, Marsolais EB. Electrically induced gait changes post stroke. J Neuro Rehab. 199;37:17–25.

Waters RL, Campbell J, Thomas L, Hugaos L, Davis P. Energy cost of walking in lower extremity casts. J Bone Joint Surg. 1982; 64:896–899.

Dobkin BH. An overview of treadmill locomotor training with partial body weight support: a neurophysiological sound approach whose time has come for randomized clinical trials. Neurorehabil Neural Repair 1999; 13:157–165.

Dobkin BH. "Strategies for stroke rehabilitation", Lancet Neurol. 2004; 3(9):528-536.

Glanz M, Klawansky S, Stason W, Berkey C, ,Thomas C. Chalmers, A Functional Electrostimulation in Poststroke Rehabilitation: A Meta-Analysis of the Randomized Controlled Trials, Arch Phys Med Rehabil1996 Jun;77(6):549-53

Hesse S, Bertelt C, Jahnke MT, et al. Treadmill training with partial body weight support as compared to physiotherapy in non-ambulatory hemiparetic patients. Stroke 1995; 26:976–981.

Hesse S, Helm B, Krajnik J, Gregoric M, Mauritz KH. Treadmill training with partial body weight support: influence of body weight release on the gait of hemiparetic patients. J Neurol Rehabil 1997;11:
15– 20.

Hesse S, Uhlenbrock D, Werner C, Bardeleben A. A mechanized gait trainer for restoring gait in nonambulatory subjects. Arch Phys Med Rehabil. 2000; 81: 1158–1161.

Hidler J, Nichols D, Pelliccio M, Brady K, Campbell DD, Kahn JH, Hornby TG. Multicenter randomized clinical trial evaluating the effectiveness of the Lokomat in subacute stroke. Neurorehabil Neural Repair 2009; 23:5-13.

Hornby TG, Campbell DD, Kahn JH, Demott T, Moore JL, Roth HR. Enhanced gait-related improvements after therapist- versus robotic-assisted locomotor training in subjects with chronic stroke: a randomized controlled study. Stroke 2008; 39:1786-92.

Forner Cordero A., Steyvers M., Levin O., Alaerts K, and Swinnen S.P."Changes in cortico motor excitability following prolonged muscle tendon vibration"Behav Brain Reser., 190(1), 41-9, 2008

Ivanenko YP, Poppele RE, Lacquaniti F. 2004. Five basic muscle activation patterns account for muscle activity during human locomotion. J Physiol 556:267–82.

Ivanenko YP, Poppele RE, Lacquaniti F. 2006. Spinal cord maps of spatiotemporal alpha-motoneuron activation in humans walking at different speeds. J Neurophysiol 95(2):602–18.

Ivanenko YP, Wright WG, Gurfinkel VS, Horak F, Cordo P. 2006.Interaction of involuntary post-contraction activity with locomotor movements. Exp Brain Res 169(2):255–60.

Kollen B.J, Lennon B, Lyons L, Wheatlez-Smith M, ScheperM, Buurke J.H, Halfens J, Geurts A.C and Kwakkel"The Effectivnes of the Bobath Concept in Stroke Rehabilitation. What is the evidence? Stroke, 29, 2009

Kosak MC, Reding MJ. Comparison of partial body weight-supported treadmill gait training versus aggressive bracing assisted walking post stroke. Neurorehabilitation Neural Repair 2000; 14(1):13 –9

Matjačić, Z. Johannesen I. J., and Sinkjær T., "A multi-purpose rehabilitation frame: A novel apparatus for balance training during standing of neurologically impaired individuals," J. Rehabil. Res. Dev., 2000, vol 37(6), pp. 681-692.

Mayo NE, Wood-Dauphinee S, Ahmed S, Gordon C, Higgins J, McEwen S, Salbach N. Disablement following stroke. Disabil Rehabil. 1999; 21:258–268

McCain KJ, Pollo FE, Baum BS, Coleman SC, Baker S, Smith PS. Locomotor treadmill training with partial body-weight support before overground gait in adults with acute stroke: a pilot study. Arch Phys Med Rehabil. 2008; 89:684–691.

Mehrholz J, Werner C, Kugler J, Pohl M. Electromechanical-assisted training for walking after stroke. Cochrane Database of Systematic Reviews 2007, Issue 4. Art. No.: CD006185. DOI: 10.1002/14651858.CD006185.pub2

Moseley AM, Stark A, Cameron ID, Pollock A. Treadmill training and body-weight support for walking after stroke. Cochrane Database Syst Rev. 2003;(3):CD002840.

Liberson W, Holmquest H, and Scott M, "Functional electrotherapy: Stimulation of the common peroneal nerve synchronized with the swing phase of gait of hemiplegic subjects," Arch. Phys. Med. Rehabil., vol. 42 pp. 202-205, 1961.

Pohl M, Werner C, Holzgraefe M, Kroczek G, Mehrholz J, Wingendorf I, Hoolig G, Koch R, Hesse S. Repetitive locomotor training and physiotherapy improve walking and basic activities of daily living after stroke: a single-blind, randomized multicentre trial (DEutsche GAngtrainerStudie, DEGAS). Clin Rehabil. 2007; 21: 17-27.

Popovic DB, Sinkjær T, Control of Movement for the Physically Disabled. Springer, London, 2000; 259-268.

Popović D. B. , Popović M. B Schwirtlich., L., Grey M. Mazzaro N., and Sinkjær T., "Functional Electrical Therapy of walking: pilot study," Proc. 10th Ann. Conf. Intern. Soc. IFESS, Montreal, Canada, 2005 June 5-15, 2005, pp. 86-88.

Popovic DB, Sinkjær T, Control of Movement for the Physically Disabled. Springer, London, July 2000.

Popovic MB, Popovic DB, Sinkjær T, Stefanovic A, Schwirtlich L. "Clinical evaluation of functional electrical therapy in acute hemiplegic subjects". J Rehabil Res Dev 2003; 40:443-453.

Popović DB, Radulović M, Schwirtlich L, Jauković N. Automatic vs. hand-controlled walking of paraplegics. Med Eng Phys. 25:63-74, 2003.

Sullivan KJ, Knowlton BJ, Dobkin BH. Step training with body weight support: effect of treadmill speed and practice paradigms on poststroke locomotor recovery. Arch Phys Med Rehabil 2002; 83(5):683– 91.

Taub E, Miller NE, Novak TA, et al. Technique to improve chronic motor deficit after stroke. Arch Phys Med Rehabil 1993; 74:347–354

Teixeira da Cunha Filho I, Lim PA, Qureshy H, Henson H, Monga T,Protas EJ. A comparison of regular rehabilitation and regular rehabilitation with supported treadmill ambulation training for acute stroke patients. J Rehabil Res Dev 2001 (Mar–Apr);38(2):245–55.

Tiebin Yan, Hui Chan Christina W. and Leonard S.W.Li.Functional electrical stimulation improves motor recovery of the lower extremity and walking ability of subjects with first acute stroke.Stroke2005; 36; 80-884.

Trueblood PR. Partial body weight treadmill training in persons with chronic stroke. Neurorehabilitation 2001; 16(3):141– 53.

Veg A, Popović DB. Walkaround: mobile balance support for therapy of walking. IEEE Trans Neural Syst Rehabil Eng. 2008 Jun; 16(3):264-9

Visintin M, Barbeau H, Korner-Bitensky N, Mato N. A new approach to retrain gait in stroke patients through body weight support and treadmill stimulation. Stroke 1998; 29:1122–8.

Visintin M, Barbeau H. The effects of parallel bars, body weight support and speed on the modulation of the locomotor pattern of spastic paretic gait. A preliminary communication. Paraplegia 1994; 32(8):540– 53

Zhu XJ, Wang T, Chen Q et al. The effects of standardized rehabilitation treatment on the outcome of activities of daily living in patients with hemiplegia after stroke. Chinese Journal of Cerebrovascular Diseases. 2007; 4:254-259.

Weber DJ, Stein RB, Chan KM et al. BIONicWalkAide for correcting foot drop. IEEE Trans Neural Syst Rehabil Eng 2005:242–246

There is sufficient evidence that the CNS can alter its structure and have plastic changes induced by continued sensory stimulation or by repeated activity (Forner Cordero, 2008). Neural plasticity plays a key role in recovery from damage in the nervous system (Beherman, 2006). The principles of motor relearning to induce CNS activity dependent changes are 1. the repetition of desired motion and coordination patterns accompanied by the corresponding muscle activation and 2. sensory feedback. (Dally, 2007). Moreover it is very important the focused attention and intention of the patient while performing the movement and the resulting neural reward mechanisms when achieving the goal, (Dobkin, 2004). Also important is the number of the sessions and the repetitions in each session, yet not being clear which is the optimal number and duration of the treatment. Neural plasticity can be due to central mechanisms or peripheral mechanisms. There is an important cortical involment in the control of human gait and plastic changes occur at this level in stroke patients (Nielsen J.B., 2003).However, knowledge about the motor control organization of human gait control is incomplete and the assumptions taken from the therapy based on the current views about the human motor system lead to paradoxical results.

Studies in rehabilitation of hand reaching and grasping (Popovic et al.2003) have shown that the recovery of acute stroke patients is greatly promoted when using FET.FET was applied 30 min daily for 3 weeks. Forty-one acute hemiplegics volunteered in the 18-months single blinded cross-over study. Nineteen patients (Group A) participated in FET during their acute hemiplegia, and 22 patients (Group B) participated in FET during their chronic phase of hemiplegia. Group B patients were controls during FET in acute hemiplegia, and Group A patients were controls during the FET in chronic hemiplegia. Thirty-two patients completed the study. The outcomes of the Upper Extremity Function Test (UEFT) were used to assess the ability of patients to functionally use objects, as were the Drawing Test (DT) (used to assess the coordination of the arm), the Modified Ashworth Scale, the range of movement, and the questionnaire estimating the patients' satisfaction with the usage of the paretic arm.Patients who participated in the FET during the acute phase of hemiplegia (Group A) reached functionality of the paretic arm, on average, in less than 6 weeks, and maintained this near-normal use of the arm and hand throughout the follow-up. The gains in all outcome scores were significantly larger in Group A after FET and at all follow-ups compared with the scores before the treatment. The gains in patients who participated in the FET in the chronic phase of hemiplegia (Group B) were measurable, yet not significant. The speed of recovery was larger during the period of the FET compared with the follow-up period. The gains in Group A were significantly larger compared with the gains in Group B. The FET greatly promotes the recovery of the paretic arm if applied during the acute phase of post-stroke.

This findings indicated that that FET combined with early rehabilitation is very important in accelerating the recovery of motor function, improving the ability and thereby the quality of life. This motivated us to extent that application to the lower limbs.

RESEARCH CHALLENGES

1. Develop new method for multi-channel electrical stimulation which augments both stance and swing phases of the gait cycle and uses feedback from simple sensors system

New sensors-driven multi-channel electrical stimulation can facilitate the near-normal walking; thereby, allow training of the near normal walking. This facilitation allows intensive exercise of walking and also provides a strong input to central nervous system that is phased into the near-normal physical activity caused by electrical stimulation and activities that follow the stimulation. The improvements of the walking are consequence of the stronger muscles due to the exercise, but more due to reorganization of central nervous system at cortical and spinal levels.

2. Is the FET of walking in individuals with acute hemiplegia more effective compared with conventional rehabilitation?

Many studies reviled that 2 therapies are better than single one. The problems still remain. When to start? Which therapies to combine?

In designing clinical studies it's important to integrate as many patients to test the new tool, but the problem is that what work in one can leave us with no respond in another ones. Thus we tried to concentrate on functional similar type of stroke, and more important similar functional status, with similar duration after accident and to tolerate electrical stimulation, which I guess most would agree it's not easy to find in acute stage.

3. Assess in the randomized clinical study the differences in functionality and disability before and after the treatment

We decided to implement most commonly used tests for evaluation of functional status in clinical observation.Fugl Mayer Score, Barthel Index and Berg balance Scale. After clinical evaluation we had to go on the next level and that broth us to the main point of the research and that is:

4. What are the main neurophysiological mechanisms behind the improved functionality?

Knowledge about the related mechanisms is important to expand the understanding of pathophysiology in order to help predicting the patient's prognosis, and to develop new therapeutic and interventional strategies (Liepert et al. 2004) but also to see how to best utilize the ones that are available in realtime.

We decided to explore the role of poly EMG, as a tool in quantification of the recovery process and functional changes as a consequence of functional outcome due to recovery process after the therapy.

These objectives were studied in research studies

- *Study 1. Kojovic, Jovana ; Djuric-Jovicic, Milica ; Dosen Strahinja ; Popovic, Mirjana B; Popovic, Dejan B. Sensor-driven four-channel stimulation of paretic leg: functional electrical walking therapy. Journal of Neuroscience Methods. 2009; 181(1): 100-105*
- *Study 2.Kojovic J, Miljkovic N, Jankovic M, Popovic D Recovery of motor function after stroke: a polymyography-based analysis Journal of Neuroscience Methods. Vol. 194, No. 2, 2011, p. 321-328*

Chapter 2

Sensor-Driven Four-Channel Stimulation of Paretic Leg: Functional Electrical Walking Therapy

Gait rehabilitation in patients with severe hemiplegia requires substantial effort. Contemporary FES systems for hemiplegic gait are mostly considering the drop-foot syndrome. However, the drop-foot is only the most prominent deficiency that limits the walking. Hemiplegia also affects hip and knee flexion and extension of the paretic leg, and often leads to crouched walking with major asymmetry. The impaired leg affects and changes the movement of the nonparetic leg. Therefore, it is of interest to provide better assistance of walking in individuals with hemiplegia in order to increase the walking speed and symmetry. The purpose of this study was to develop and test gait training method with multi channel functional electrical stimulation sensors driven that potentially could provide a practice pattern that was close to normal and afforded multiple repetitions of the desired pattern.

PHASE1.BUILDING OF THE SYSTEM

We recorded data from non affected leg of patients with hemiplegia and surface EMG from quadriceps, hamstrings, tibialis anterior, and soleus muscles, following recommendation of SENIAM.

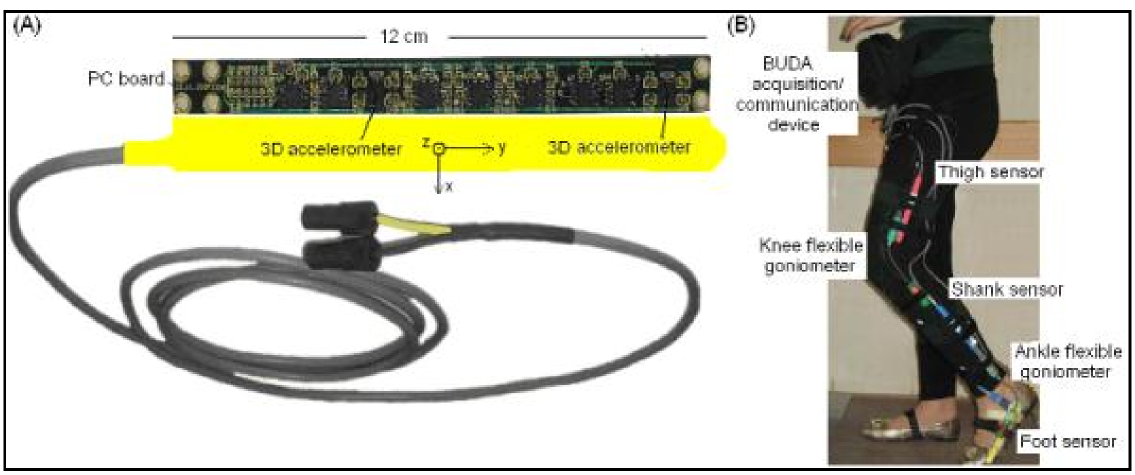


Figure2.1.The set up of experiment

The input data in this case were signals coming from accelerometers and force sensing resistors, and the output data were patterns of muscle activities (EMG). The input data come from two accelerometers

(ADXL203, Analog Devices, US) aligned along the shank of the paretic leg at a distance of 14 cm, one force-sensing resistor (Interlink Electronics, US) mounted into the heel zone of the insole of the paretic leg, and one force-sensing resistor mounted in the metatarsal zone of the insole of the non-paretic leg (Fig. 1).

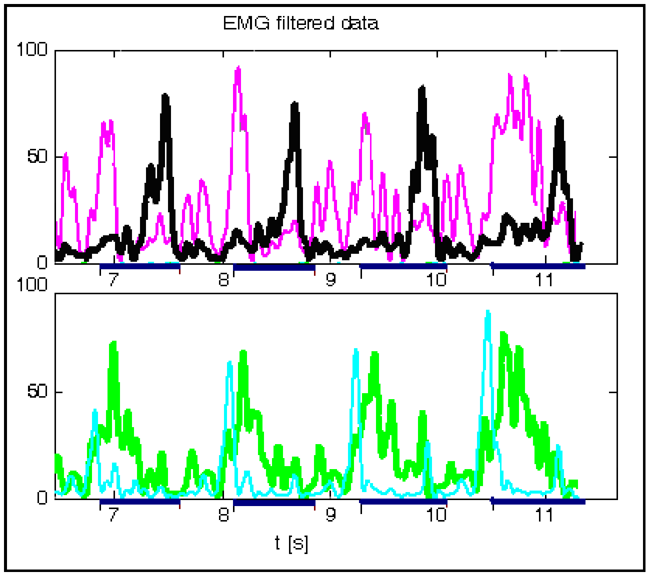


Figure2.2.filtered EMG signals from TA (black line), SOL (pink line), RF (green line), and HAM (blue line)

Both input and output data were translated into binary signals by implementing a threshold method. The output data threshold was set at 15% of the maximum activity recorded with bipolar electrodes from recorded muscles.

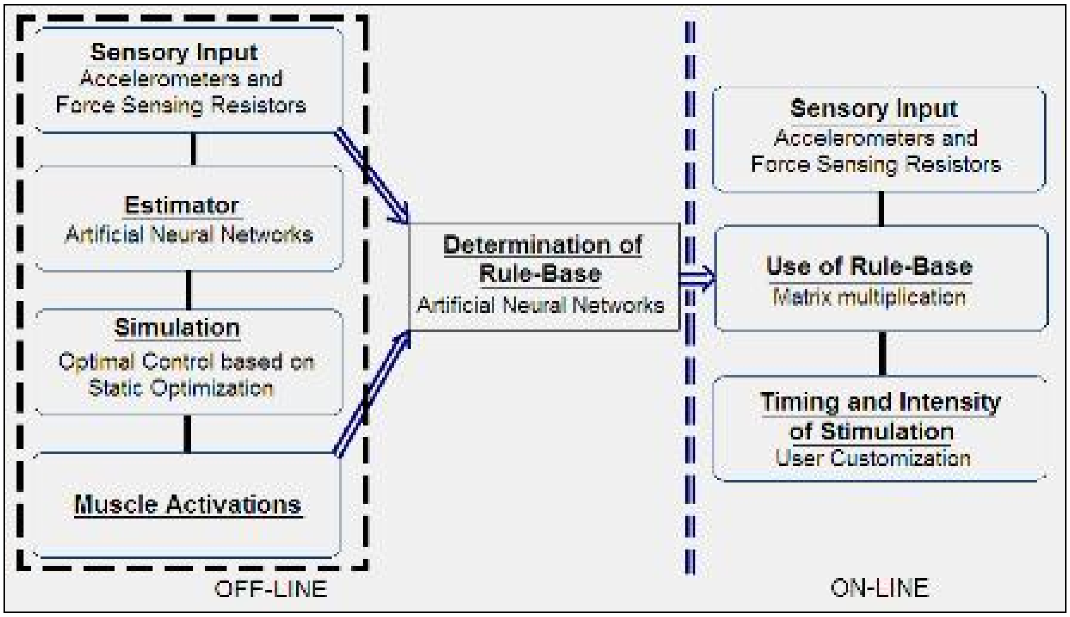


Figure 2.3.The inductive learning was applied for mapping. Inductive learning is a method that minimizes the entropy and results with IF-THEN rules. The IF-THEN rules were created by mapping the input-output by means of machine learning.

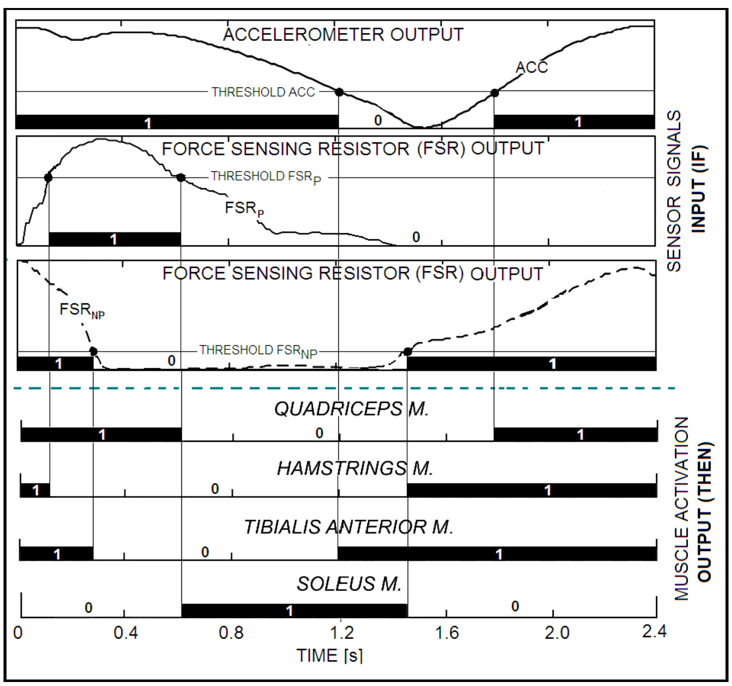


Figure 2.4: The four bottom panels show the intervals (black bars) when the EMG recorded from the non-affected leg of stroke patient during one gait cycle was above 15% of the maximum EMG signal from the same muscle during the gait cycle. The top three panels show sensor signals and the intervals determined by machine learning (black bars) for control of stimulation.

Phase 2.Testing in the clinical trial

Before an adequate program of therapy was prescribed, each subject's status was assessed and his or her past medical history, social history, and communication skills were evaluated.

This assessment of the subject's status comprised information about the subject's functional level (reflex status, range of motion, coordination, sensation/perception, voluntary control, and activities in changing the positions [eg, standing up, sitting down, getting out of bed] 1, with special emphasis on gait evaluation. The subject's functional abilities, or abilities to perform different movements or tasks (eg, pattern movements, selective movements, standing up, maintaining standing, walking) were the basis for treatment. There was no general pattern of therapy that would apply to all subjects. Each subject received the therapy adapted to his or her abilities, deficiencies, and needs. The same therapists worked with an individual subject throughout the program of conventional treatment. In general, the conventional treatment consisted of a passive and active approach.

In addition we applied the surface electrical stimulation on the peroneal nerve for ankle dorsiflexion, the soleus muscle for ankle plantar flexion, the hamstring muscles (biceps femoris, semitendinosus, semimembranosus) for knee flexion, the quadriceps femoris musculature (rectus femoris, vastus medialis,vastus lateralis) for knee extension.

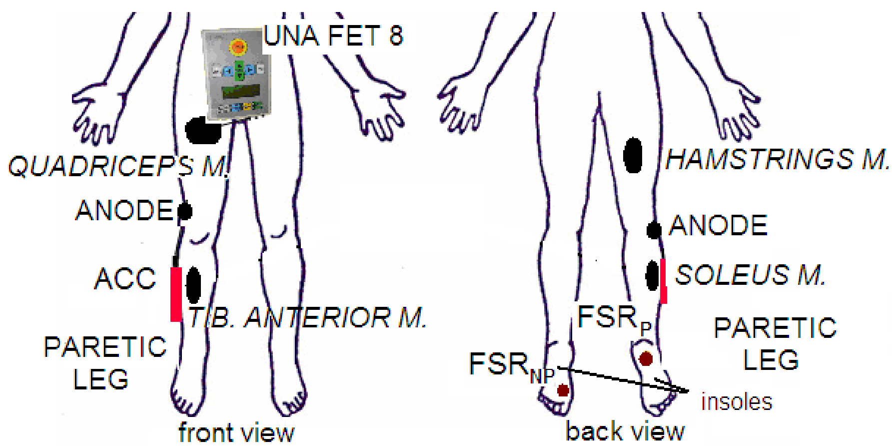


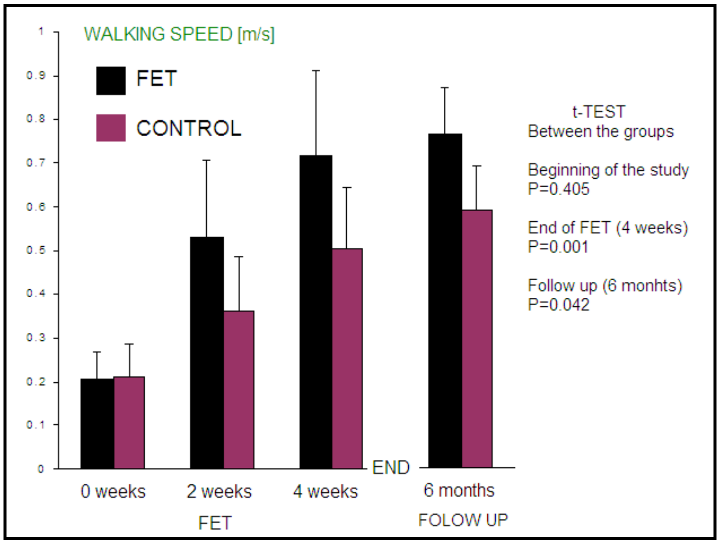
Figure 2.5.: Sketch of the four-channel assistive system based on the UNA FET 8 stimulator and four sensors for controlling four muscle groups during walking. FSR – Force-Sensing Resistor (NP- nonparetic, P-paretic), ACC – two accelerometers aligned along the shank on a small rod.

An individualized stimulation sequence was determined for each subject, starting with a general initial pattern and modifying it during the first couple of stimulation sessions. The stimulator supports various stimulation paradigms and can generate bursts of pulses with the following parameters: frequency f = 5 - 100 Hz, pulse duration T = 10 - 1000 μs, rise and fall times when starting and stopping stimulation from 0 to 0.5 seconds, and the pulse amplitude I = 0 - 50 mA.The parameters were set for each patient individually and changed during the therapy.

The subjects walked on a 100-m walkway. At the beginning of therapy the subjects walked a short distance, walking again after a rest period. The initial distance depended on the subject's ability to avoid over-exertion, or it was determined by the subject's physician. During the course of treatment, the distance was gradually increased. The subjects, however, were instructed not to ambulate more than 500 m per session because they had to save some strength to participate in other rehabilitation programs. The measurements were divided into two levels: measurement of biomechanical variables of gait and assessment of the physical status of the subject according to the Fugl-Meyer scale and Barhel Index. Measurement of biomechanical variables of gait comprised measurement of the gait speed and ground reaction forces. On the other hand, we dealt with severely involved patients. We instructed our subjects to walk at their preferred speed.

Results

Results obtained from patients at first day and at follows up at 4 weeks and after 6 months concerning walking speed and walking symmetry are presented. It could be observed that there were no big discrepancies between the groups at the baseline of measurement .However our results indicate significant improvement and benefit from the FET treatment and its carry over effect (it could be noticed then even after 6 months the improvements as a consequence of therapy are remained and efficacy of speed and symmetry increased in comparison with the end of therapy (week 4)).



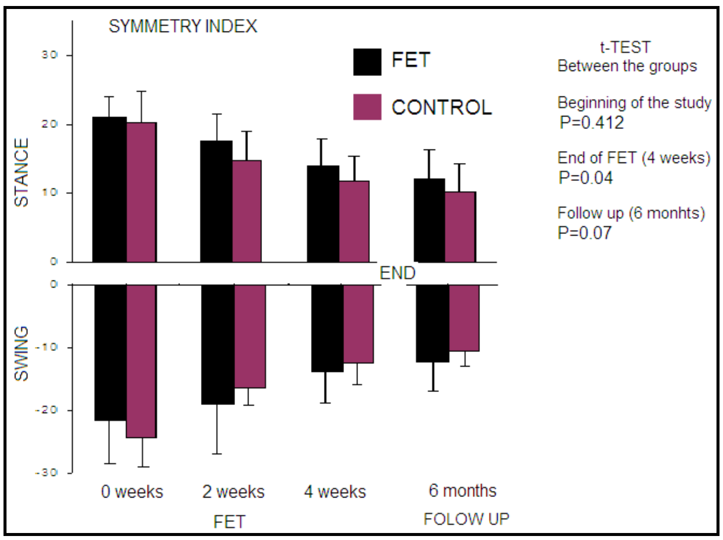


Figure 2.6. Differences of walking speed and symmetry index at the baseline , 2 weeks and ,at the end of treatment(4 weeks) and at 6 months follow up for FET (black bars) and CON (violet bars)

The symmetry index was estimated for the stance or swing phase and for the whole stride as follows:

$$SI[\%] = \left[1 - 2\frac{T_{paretic} - T_{nonparetic}}{T_{paretic} + T_{nonparetic}}\right] \cdot 100$$

where terms Tparetic and Tnonparetic are the duration of the gait phases for the paretic and nonparetic legs. The ideal SI is 100. The gait speed and symmetry index were assessed while patients covered a distance of 6 meters. In this study, we present the SI for the stance phase

- Results form the other tested parameters could be found in the attached paper (Kojovic, Jovana ; Djuric-Jovicic, Milica ; Dosen Strahinja ; Popovic, Mirjana B; Popovic, Dejan B. Sensor-driven four-channel stimulation of paretic leg: functional electrical walking therapy. Journal of Neuroscience Methods. 2009; 181(1): 100-105)

DISCUSSION

The results of our study are in line with the findings of Yan et al. (2005) who applied multi-channel stimulation in acute stroke patients. The treatment in that study was electrical stimulation of leg muscles in patients while they were laying and the paretic leg was supported by a sling. The therapy introduced by Yan et al. showed improved motor recovery and functional mobility. Patients in their FET group showed greater improvement compared with the control groups in terms of lower-limb strength, mobility, ambulation ability, walking speed, and activities in daily living after 4 weeks and 6 months follow-up. The common finding between the study of Yan and this study is that electrical stimulation in the acute phase contributes to recovery. Four weeks of therapy in all patients from the FET group resulted with independent walking, while only 2 out of 6 patients in the CON group reached independent slow walking.

When we are looking for an explanation as to why multi channel electrical stimulation combined with traditional is more successful, than conventional therapy alone, we contend that it might works on two levels: direct and indirect. The direct effects are functional movement as a result of muscle contraction induced by functional electrical stimulation, corrected synergistic movements, better coordination of the extremities, better security and self-confidence of the patient, and starting gait training immediately at the beginning of therapy. We contend that the indirect effects are improved and richer sensory feedback information to the CNS and despite the large possible enhancement of CNS plastic- heterogeneity of the hemiplegic popuity,better and faster motor learning, highly significant statistical and high motivation to participate in results were obtained the program.

We are aware that this finding has limited value since it was impossible to individually assess the contribution of spontaneous recovery. So, we however need multi center trials to support this hypothesis.

References

Bijak M, Rakos M, Hofer C, Mayr W, Strohhofer M, Raschka D, Kern H. Stimulation Parameter Optimization for FES Supported Standing up and Walking in SCI Patients, Artif Organs 2005; 29(3):220-3

Burridge JH. Does the drop-foot stimulator improve walking in hemiplegia? Neuromod 2001; 4:77-83.

Daly JJ, Ruff R, Haycook K, Strasshofer B, Marsolais EB, Dobos L. Feasibility of gait training for acute stroke patients using FNS with implanted electrodes. J Neurol Sci 2000; 179:103–7

Daly JJ, Ruff RL. Feasibility of combining multi-channel functional neuromuscular stimulation with weight-supported treadmill training. J Neurol Sci 2004; 225:105-15.

Daly JJ, Roenigk K, Holcomb J, Rogers JM, Butler K, Gansen J, McCabe J, Fredrickson E, Marsolais EB, Ruff RL. A Randomized Controlled Trial of Functional Neuromuscular Stimulation in Chronic Stroke Subjects. Stroke 2006; 37:172-8;

DietzV.Good clinical practice in neurorehabilitation, http://neurology.thelancet.com 2006; 5: 377-8.

Dohring ME, Daly JJ. Automatic Synchronization of Functional Electrical Stimulation and Robotic Assisted Treadmill Training. IEEE Trans Neur Syst Rehab Eng 2008, TNSRE-16(3): 310-3.

Došen S. FET Studio - software system for support of functional electrical therapy. J Automat Control, Univ. Belgrade, 2005; 15: 31-4.

Duncan P, Studenski S, Richards L, Gollub S, Lai SM, Reker D, Perera S, Yates J, Koch V, Rigler S, Johnson D. Randomized clinical trial of therapeutic exercise in subacute stroke. Stroke 2003; 34:2173–80

Gladstone DJ, Danells CJ, Black SE. The Fugl-Meyer Assessment of Motor Recovery after Stroke: A Critical Review of Its Measurement Properties. Neurorehabil Neural Repair 2002; 16:232-40

Jonić S, Janković T, Gajić V, Popović DB. Three machine learning techniques for automatic determination of rules to control locomotion. IEEE Trans Biomed Eng 1999; 46(3):300-10.

Jorgensen HS, Nakayama H, Raaschou HO, Olsen TS. Recovery of walking function in stroke patients: The Copenhagen Stroke Study. Arch Phys Med Rehabil 1995; 76(1):27–32.

Kostov A, Andrews BJ, Popović DB, Stein RB and Armstrong WW. Machine learning in control of functional electrical-stimulation systems for locomotion. IEEE Trans Biomed Eng 1995; 42(6):541-51.

Liberson WF, Holmquest HJ, Scott D, Dow A. Functional electrotherapy: stimulation of the peroneal nerve synchronized with the swing phase of the gait in hemiplegic patients. Arch Phys Med Rehab 1961; 42:101-5

Lyons GM, Sinkjær T, Burridge JH, Wilcox DJ. Review of Portable FES-Based Neural Orthoses for the Correction of Drop Foot. IEEE Trans Neur Syst Rehab Eng 2002; 10(4):260-79

Ng MFW, Tong RKY, Li LSW. A Pilot Study of Randomized Clinical Controlled Trial of Gait Training in Subacute Stroke Patients With Partial Body-Weight Support Electromechanical Gait Trainer and Functional Electrical Stimulation: Six-Month Follow-Up. Stroke 2008; 39; 154-60

Nikolić ZM, Popović DB. Predicting quadriceps muscle activity during gait with an automatic rule determination method. IEEE Trans Biomed Eng 1998; 45(8):1081-5.

Pitas I, Milios E, Venetsanopoulos AN. Minimum Entropy Approach to Rule Learning from Examples. IEEE Trans Sys Man Cybern 1992; SMC-22:621-35

Popović DB, Radulović M, Schwirtlich L and Jauković N. Automatic vs. hand- controlled walking of paraplegics. Med Eng Phys 2003; 25:63-74.

Popović DB, Popović MB, Sinkjær T, Stefanović A, Schwitlich L. Neuroprosthesis for therapy of paretic arm in hemiplegic subjects: A cross-over study. Can J Physiol Pharm 2004; 82:749-56.

Popović DB, Popović MB, Schwirtlich L, Grey M, Mazzaro N, Sinkjær T. Functional Electrical Therapy of Walking: Pilot Study. In Proc 10th Ann Conf Intern IFFES Society, July 2005, Montreal, Canada, pp 86-8.

Postans NJ, Hasler JP, Granat MH, Maxwell DJ. Functional Electric Stimulation to Augment Partial Weight-Bearing Supported Treadmill Training for Patients with Acute Incomplete Spinal Cord Injury: A Pilot Study. Arch Phys Med Rehabil 2004; 85:604-6

Hermens HJ, Freriks B, Merletti R, Stegeman D, et al. European recommendations for surface electromyography: results of the SENIAM project. Published by Roessingh Research and Development, Netherlands. 1999.

Stanič U, Aćimović-Janežič R, Gros N. Multichannel electrical stimulation for correction of hemiplegic gait. Methodology and preliminary results. Scand J Rehab Med 1978; 10(2):75-92.

Sulter G, Steen C, Jacques DK. Use of the Barthel Index and Modified Rankin Scale in Acute Stroke Trials. Stroke. 1999; 30:1 538-541.

Tong RKY, Ng MFW, Li LSW, So EFM. Gait Training of Patients After Stroke Using an Electromechanical Gait Trainer Combined With Simultaneous Functional Electrical Stimulation. Physical Therapy 2006; 86(9):1282-94;

Tong RK, Ng MF, Li LS. Effectiveness of Gait Training Using an Electromechanical Gait Trainer, With and Without Functional Electric Stimulation, in Subacute Stroke: A Randomized Controlled Trial. Arch Phys Med Rehabil.2006, 87:1298-1300.

Veg A, Popović DB. Walkaround®: Mobile Balance Support for Therapy of Walking. IEEE Trans. Neur. Syst. Rehab. Eng, 2008, TNSRE-16(3): 264-69

Visintin M, Barbeau H, Korner-Bitensky N, Mayo NE. A new approach to retrain gait in stroke patients through body weight support and treadmill stimulation. Stroke. 1998; 29(6):1122–28.

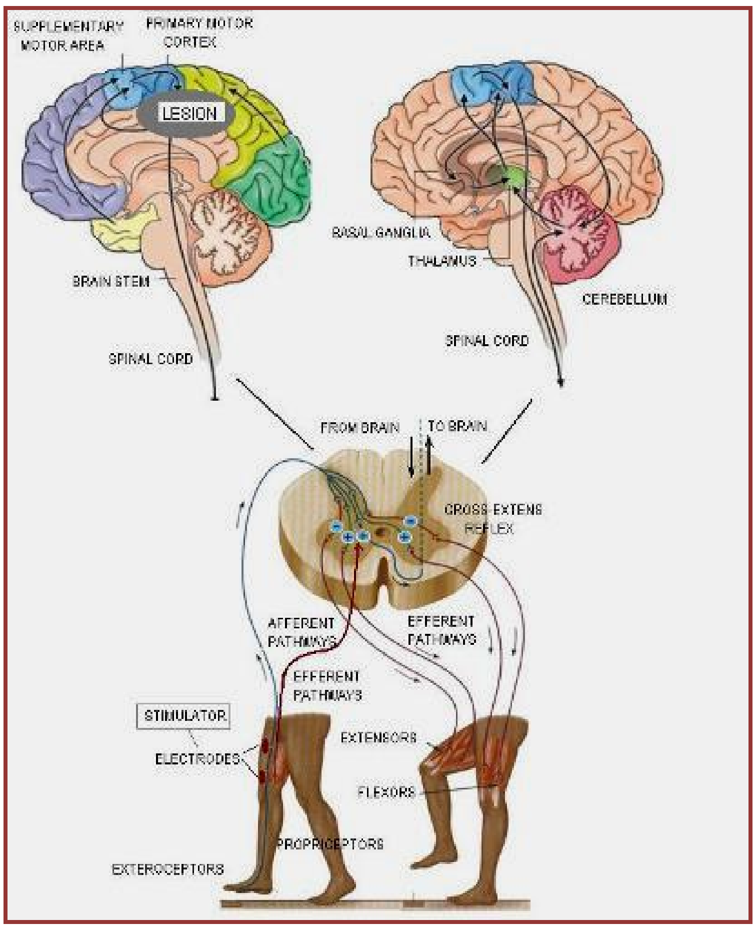
Wolpaw JR, Carp JS. Plasticity from muscle to brain. Prog Neurobiology 2006; 78(3–5):233–63.

Yan T, Hui CCC, Li SWL. Functional electrical stimulation improves motor recovery of the lower extremity and walking ability of subjects with first acute stroke. Stroke 2005; 36:80-884.

Chapter 3

Recovery of motor function after stroke: a polymiography-based analysis

In order to quantify recovery after stoke in clinical practice there are commonly used measures as Fugl Mayer, Berg Balance Scale and many others. Those methods were implemented also as a part in our research. Still none of them is sufficient to provide knowledge of the mechanism responsible for the improvements. Our previous research led us to idea that EMG analysis could be used to quantify recovery process by analyzing patterns of muscle activities before and after the therapy, and be a good tool in analysis of the recovery process together with previously mentioned measures. Studies emphasizing the role of activation patterns in the control of movement were the basis for this work (Kautz et al., 2005; d'Avella and Bizzi, 2005; Ivanenko et al., 2006; Katz et al., 2007; Clark et al., 2010; Achache et al.



.

Methods

The recordings were done at the initiation of the rehabilitation treatment and after it were completed. We asked subjects to perform dorsiflexion, as a goal directed activity. The rate of this movement was set to be rather slow in order to match the abilities of each participant (≈5 deg/s).We used as benchmark, the data obtained from 10 healthy volunteers, from which we concluded that tracking the dorsiflexion is a simple task. Subjects were asked to track the target line shown on the screen (Figure 3.1) by dorsiflexing the foot in the sitting position. The target line was created individually and automatically for each subject. The target line connected the resting ankle joint angle (0 degrees) and 90% of the maximum dorsiflexion (ϕ_{max}) angle. The achieved dorsiflexion angle, ϕ_{max} , and the target line were displayed on a monitor that faced the subject. The ϕ_{max} value was determined by averaging the recordings from 10 subsequent trials, in which subjects were asked to generate maximum dorsiflexion. The 90% of maximum dorsiflexion value was selected to minimize fatigue because we determined that the muscle forces to achieve this task were below 50% of the maximum contraction in both healthy and hemiplegic patients. The duration for the tracking task was heuristically selected to be 6 seconds, with the intention being to assess performance during slow movement.

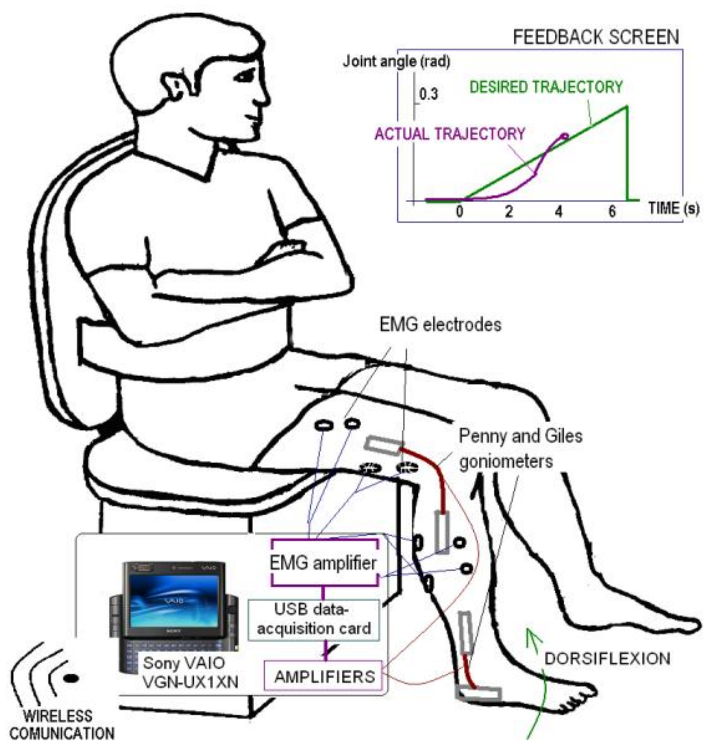


Figure 3.1.Experimental set up

The following muscles were selected for recordings: Tibialis Anterior (TA), Lateral Gastrocnemius (LG), Rectus Femoris (RF), and Biceps Femoris (BF) muscles (Figure3. 1). The recording electrodes were placed on each muscle group following the SENIAM protocol (Hermens et al., 2000).The same muscles were stimulated with multichannel electrical stimulation during the walking session of the patient and that was the reason why those muscles were selected and follow the response in the current setting.

Sensors

We used GS 26 (Bio-Medical Instruments, Warren, USA) disposable pre-gelled Ag/AgCl electrodes on the skin cleaned with an abrasive skin gel (Nuprep, Weaver & Co., CO, USA). The electrodes were connected to low-noise amplifiers with high common mode rejection ratios (CMRR > 100 dB) and with a gain of 1000 (Biovision, Wehrheim, Germany) and to the 3rd order band pass filters (3 – 500 Hz).

We used Penny & Giles flexible goniometers following the recommendations of the manufacturer (Biometrics Ltd, Gwent, UK). The goniometer at the knee joint was introduced to assess the movements of the shank with respect to the thigh (not desired).

Goniometers were positioned to the lateral side of the knee (SG110) and ankle (SG65) as shown in Figure 1.The outputs from the goniometers were connected to the joint angle unit (Angle Display Unit ADU301, Biometrics Ltd, Gwent, United Kingdom)

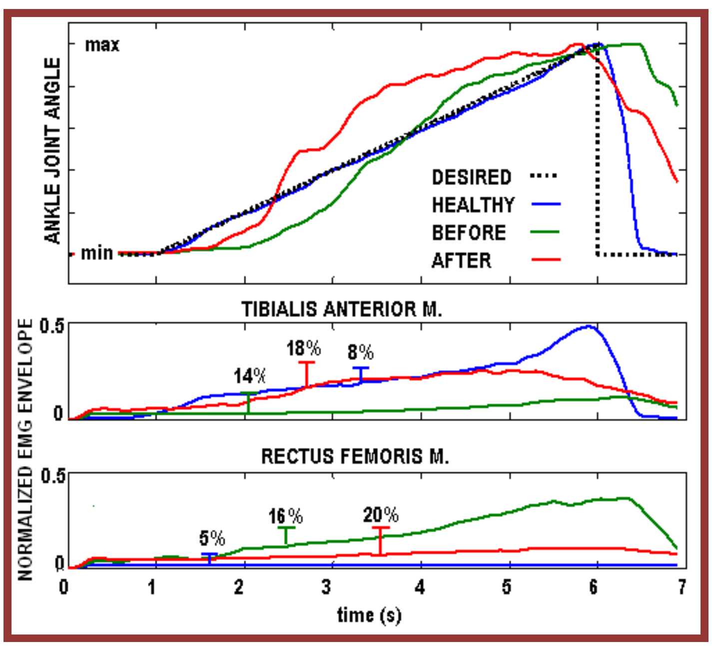


Figure 3.2 Normalized ankle angle trajectories during the tracking of dorsiflexion in healthy individuals, patients before and after the FET treatment with the reference trajectory (top panel).SD show the variability of ankle angle movements

Results

We can observe that deviation of tracking trajectory is greater in post stroke patients then in healthy individuals. FET had no influence on deviation type, but range of ankle motion was improved in FET group. Maximum ankle joint angles for patient before therapy were 12 ± 4 degrees, for patients after therapy 18 ± 5 vs. 23±5 degrees in healthy individuals

Fig. 3.3 shows the ratio of averaged median (Rm) for patients before and after the therapy with respect to the values of the healthy individuals. The differences for RF and BF are significantly different before and after therapy, Fig. 3.

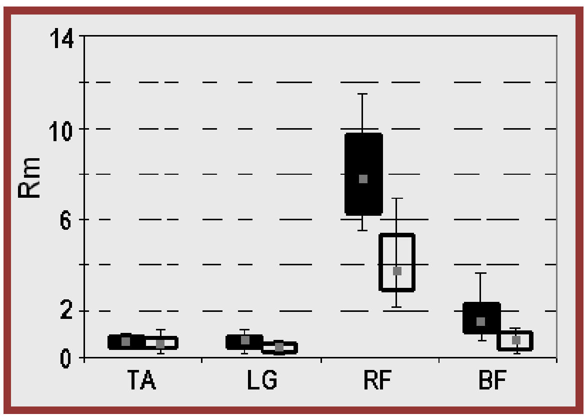


Figure 3.3: The ratio calculated between the median for subjects before (black) and after (white) the treatment. The ideal Rm value is 1. The values for TA and LG are about 0.9, while the values for the RF and BF are higher.

The tracking of the target dorsiflexion angle (maximum angle was 9±6 degrees) was delayed compared with the tracking after the therapy where the maximum angles reached values of 18±4, which is almost 80% of the values characterizing healthy subjects (Fig.3. 2; top panel). Patients before FET had low graduation of TA EMG, and in general low activation of TA in parallel with the high activation of RF, Fig. 3.2 (bottom panel) which is completely opposite compared with the healthy subjects. Patients after FET had steeper graduation of TA EMG and reached higher activation of TA, in parallel with low activation of RF. This synergy is much closer to the one characteristic for healthy subjects.

The results presented earlier suggested clearly that the rehabilitation treatment is causing the reorganization of the muscular synergies. However, we were interested in the changes in the organization of the activity during walking, not only their ability to volitionally control muscles that have been compromised due to the stroke.

Therefore, we started the analysis of the muscular activity during the walking sessions after the therapy, and compared this with the activity in the muscles before the therapy. The specific attention was given to look on both legs, since it was demonstrated in the companion study that the walking after stroke changes the walking pattern of the nonparetic leg.

We were interested to compare the EMG recordings this during the walking sessions but this proved to be impossible because of large stimulation artifacts that we were not able to eliminate. This left us with the only possibility to compare the pattern before and after the therapy. The elements that we could compare are the timings and the amplitude of the EMG signals that are normalized to the maximum voluntary activation of each of the muscles studied.

The more details could be found in attached material

Methods and materials

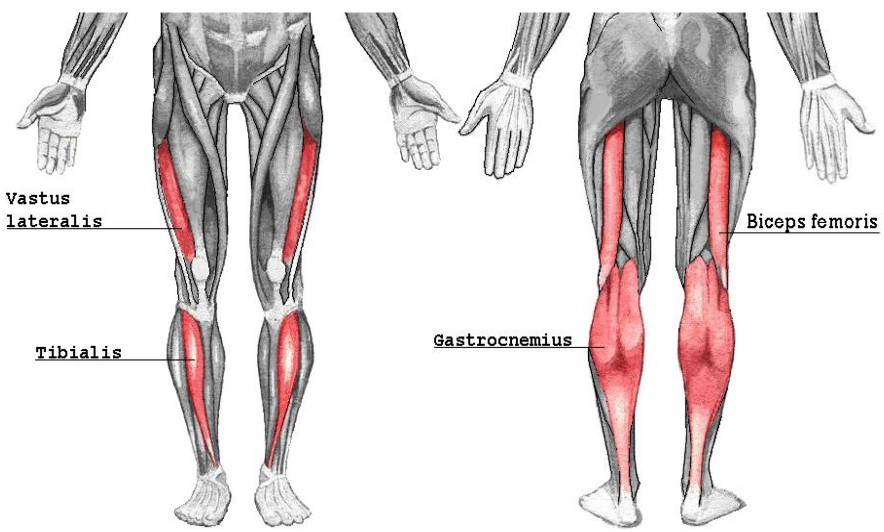


Figure 3.4: The set of the muscles analyzed in this study. TA ï tibialis anterior muscle, GM ï lateral gastrocnemius muscle, VL ï vastus lateralis muscle, and BF ï biceps femoris muscle on both paretic and non-paretic leg were considered.

Instrumentation

We recorded the surface EMG from the prime ankle and knee movers: Tibialis Anterior (TA), Lateral Gastrocnemius (GCM), Vastus lateralis (VL), and Biceps Femoris (BF) muscles (Fig.3.4). The recording electrodes were placed on each muscle group following the SENIAM protocol (Hermens et al., 2000). We *used disposable pregelled EMG Ag/AgCl electrodes with 10 mm flat pellets, (GS26, Bio-Medical Inc, Warren, USA). The EMG signals were amplified with Biovision preamplifiers (Biovision Inc, Wehrheim, Germany). The gain of the preamplifiers was set to 1000.*

Reference electrode was placed over the right knee bone.

Along with EMG we recorded signals from several Force Sensing Resistors (FSR) placed on metatarsal and heel of the sole. FSR data were decimated with factor 10. The FSR signals were recorded in order to be able to separate phases during the gait cycle.

Block diagram of the measurement system is given in Fig. 3. 5

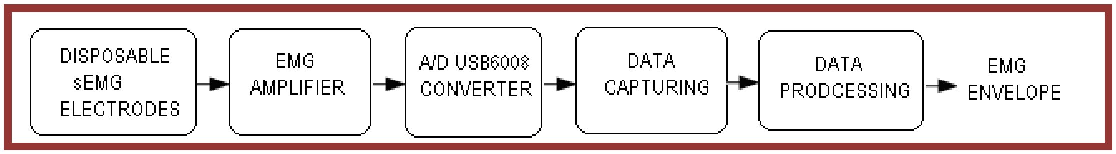


Figure 3.5: Block diagram of instrumentation and data processing

The analogue recordings were digitized with NI USB 6008 AD card, resolution of 12 bits and sampling rate of 1 kHz. The data capturing was done with a custom made application in the LabVIEW environment on a portable Sony Vaio computer (Fig. 3.6).

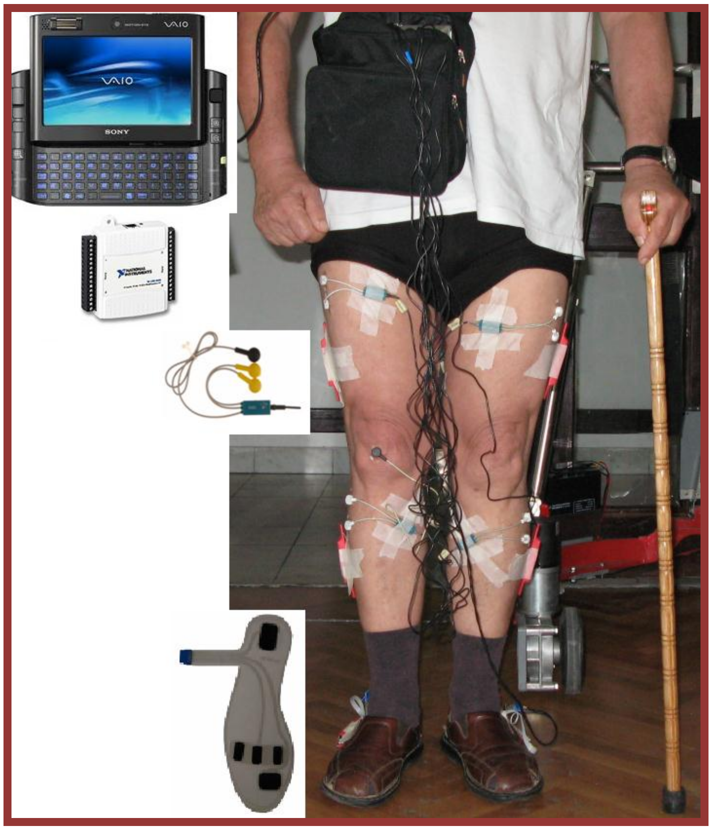


Figure 1.6: The photograph of the patient during the recording session

Procedure

Recording sessions were performed in the morning in order to minimize differences that can occur due to daily activities. Patients were asked to walk on the level ground a distance of 10 m. They covered the distance of 10 m 2 times with cane and therapist assistance. After each 10-meter walking sequence, patients were sitting and relaxing for 10 minutes.

We also recorded from five healthy individuals followed the same protocol. Healthy subjects (year matched) were asked to walk as slow speed to match the speed of the stroke patients (≈ 0.3 to 0.5 m/s).

Fig. 3.7. shows the EMG activities of a stroke patient with good improvement of walking. The left panels show the non paretic leg, while the right panels the paretic leg. The EMG activity was superimposed over the activities characteristic for healthy individuals walking at similar speed.

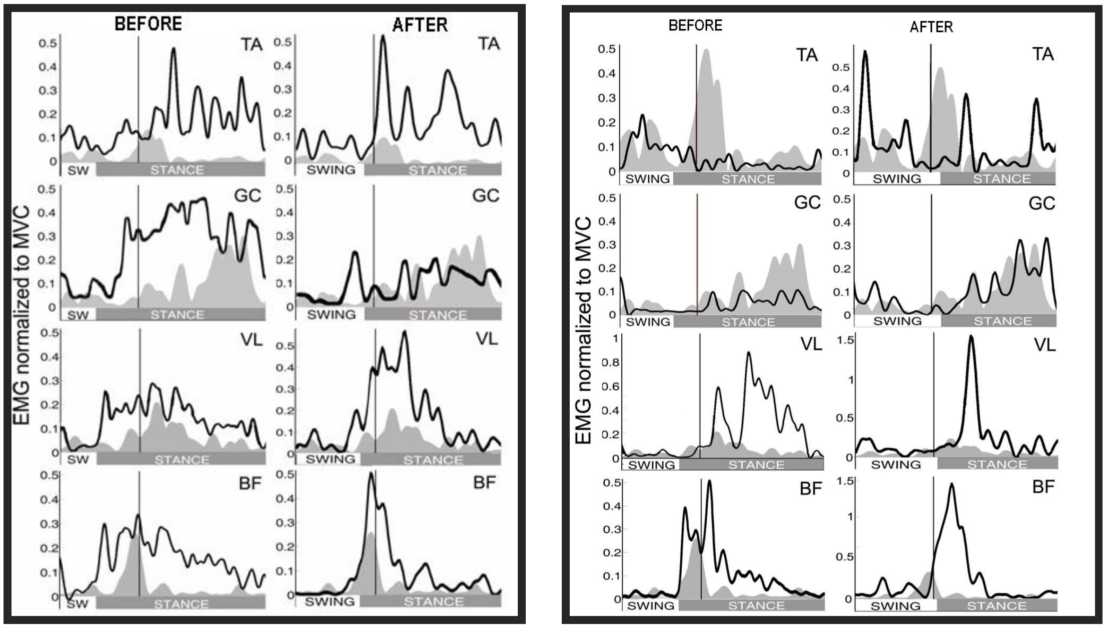


Figure 3.7: The envelopes of EMG activities for the patient with good recovery of gait after the FET. Left panels show the recordings from the nonparetic leg, while the right panels the recordings from the paretic leg. The vertical lines show the end of swing phase of the gait cycle.

The analysis of the recordings for the group that participated in our study whose that ratio of the swing to stance phase of gait improved for 22±11% in the nonparetic leg compared to the ratio characteristic for healthy, and 19±14% for the paretic leg. The timing (onset and offset) of the EMG activity measured as 10% of the maximum activity improved in the paretic leg, however deteriorated in the nonparetic leg. This suggests that the new strategy for gait that patients prefer it less healthy like. This finding is consistent over both groups. The results are very heterogeneous and it was not suitable to perform statistical analysis. This study is still in progress and comprehensive results will be disseminated at later time.

References

Achache V, Mazevet D, Iglesias C, Lackmy A, Nielsen JB, Katz R, Marchand-Pauvert V.Enhanced spinal excitation from ankle flexors to knee extensors during walking in stroke patients. Clin Neurophysiol. 2010 Jun; 121(6):930-8.

Carey JR, Anderson KM, Kimberley TJ, Lewis SM, Auerbach EJ, Ugurbil K. fMRI analysis of ankle movement tracking training in subject with stroke. Exp Brain Res. 2004 Feb; 154(3):281-90.

Clark DJ, Ting LH, Zajac FE, Neptune RR, Kautz SA. Merging of healthy motor modules predicts reduced locomotor performance and muscle coordination complexity post-stroke. JNeurophysiol. 2010 Feb; 103(2):844-57.

Daly JJ. Ruff RL. Feasibility of combining multi-channel functional neuromuscular stimulation with weight-supported treadmill training. J Neurol Sci. 2004; 225:105-15.

Daly JJ, Sng K, Roenigk K, Fredrickson E, Dohring M. Intra-limb coordination deficit in stroke survivors and response to treatment. Gait Posture. 2007 Mar; 25(3):412-8.

D'Avella A, Bizzi E. Shared and specific muscle synergies in natural motor behaviors. Proc.Natl Acad Sci U S A. 2005 Feb 22; 102(8):3076-81.

Dean CM, Ada L, Bampton J, Morris ME, Katrak PH, Potts S. Treadmill walking with bodyweight support in subacute non ambulatory stroke improves walking capacity more than overground walking: a randomized trial. J Physiother. 2010; 56(2):97-103.

Dobkin BH, Firestine A, West M, Saremi K, Woods R. Ankle dorsiflexion as an fMRI paradigm to assay motor control for walking during rehabilitation. Neuroimage. 2004 Sep; 23(1):370-81.

Ebenbichler G. Dynamic EMG: a clinician's perspective. IEEE Eng Med Biol Mag. 2001; 20(6):34–5.

Embrey DG, Holtz SL, Alon G, Brandsma BA, McCoy SW. Functional electrical stimulation to dorsiflexors and plantar flexors during gait to improve walking in adults with chronic hemiplegia. Arch Phys Med Rehabil. 2010 May; 91(5):687-96.

Enzinger C, Johansen-Berg H, Dawes H, Bogdanovic M, Collett J, Guy C, Ropele S, KischkaU, Wade D, Fazekas F, Matthews PM. Functional MRI correlates of lower limb function in stroke victims with gait impairment. Stroke. 2008 May; 39(5):1507-13

Enzinger C, Dawes H, Johansen-Berg H, Wade D, Bogdanovic M, Collett J, Guy C, KischkaU, Ropele S, Fazekas F, Matthews PM. Brain activity changes associated with treadmill training after stroke. Stroke. 2009 Jul; 40(7):2460-7.

Everaert DG, Thompson AK, Chong SL, Stein RB. Does functional electrical stimulation for foot drop strengthen corticospinal connections? Neurorehabil Neural Repair. 2010 Feb; 24(2):168-77.

Georgakis A, Stergioulas LK, Giakas G. Fatigue analysis of the surface EMG signal in isometric constant force contractions using the averaged instantaneous frequency. IEEE TransBiomed Eng 2003 Feb; 50(2):262–5.

Hermens HJ, Freriks B, Disselhorst-Klug C, Rau G., Development of recommendations for SEMG sensors and sensor placement procedures. J Electromyog and Kinesiol. 2000 Oct; 10(5):361-74.

Hesse S, Werner C, von Frankenberg S, Bardeleben A., Treadmill training with partial body weight support after stroke. Phys Med Rehabil Clin N Am. 2003 Feb; 14(1 Suppl):S111-23.

Ivanenko YP, Poppele RE, Lacquaniti F. Motor control programs and walking.Neuroscientist. 2006 Aug; 12(4):339-48.

Ivey FM, Hafer-Macko CE, Macko RF. Task-oriented treadmill exercise training in chronic hemiparetic stroke. J Rehabil Res Dev. 2008 Feb; 45(2):249-59.

Katz A, Tirosh E, Marmur R, Mizrahi J. Enhancement of muscle activity by electrical stimulation in cerebral palsy: A case-control study. J Child Neurol. 2008 Dec; 23(3):259-267;

Kato H, Izumiyama M, Koizumi H, Takahashi A, Itoyama Y. Near-infrared spectroscopic topography as a tool to monitor motor reorganization after hemiparetic stroke: a comparison with functional MRI. Stroke. 2002 Aug; 33(8):2032-6.

Kautz SA, Duncan PW, Perera S, Neptune RR, Studenski SA. Coordination of hemiparetic locomotion after stroke rehabilitation. Neurorehabil Neural Repair. 2005 Sep; 19(3):250-8.

Kesar TM, Perumal R, Jancosko A, Reisman DS, Rudolph KS, Higginson JS, Binder-Macleod SA. Novel patterns of functional electrical stimulation have an immediate effect on dorsiflexor muscle function during gait for people poststroke. Phys Ther. 2010 Jan; 90(1):55-66. Review

Knaflitz M, Bonato P. Time–frequency methods applied to muscle fatigue assessment during dynamic contractions. J Electromyogr Kines. 1999 May; 9(5):337–50.

Kojović J, Đurić-Jovičić M, Došen S, Popović MB, Popović DB, Sensor-driven four-channel stimulation of paretic leg: Functional electrical walking therapy. J Neuroscience Methods.2009 Mar;181:100-5.

Luft AR, Macko RF, Forrester LW, Villagra F, Ivey F, Sorkin JD, Whitall J, McCombe-Waller S, Katzel L, Goldberg AP, Hanley DF. Treadmill exercise activates subcortical neuralnetworks and improves walking after stroke: a randomized controlled trial. Stroke. 2008 Dec; 39(12):3341-50.

Mayr A, Kofler M, Quirbach E, Matzak H, Fröhlich K, Saltuari L. Prospective, blinded, randomized crossover study of gait rehabilitation in stroke patients using the Lokomat gait orthosis. Neurorehabil Neural Repair. 2007 Jul-Aug; 21(4):307-14.

McCain KJ, Smith PS. Locomotor treadmill training with body-weight support prior to overground gait: promoting symmetrical gait in a subject with acute stroke. Top Stroke Rehabil. 2007 Sep-Oct; 14(5):18-27.

Merletti R, Knaflitz M, DeLuca CJ. Myoelectric manifestations of fatigue in voluntary and electrically elicited contractions. J Appl Physiol. 1990; 69:1810–20.

Miljković N, Kojović J, Janković M, Popović DB. An EMG based system for assessment of recovery of movement. 2010, Proc. of the 15th IFESS, Vienna, Sep 8-12, in press.

Miyai I, Suzuki M, Hatakenaka M, Kubota K. Effect of body weight support on cortical activation during gait in patients with stroke. Exp Brain Res. 2006 Feb; 169(1):85-91.

Moritani T, DeVries HA. Neural factors versus hypertrophy in the time course of muscle strength gain. Am J Phys Med. 1979 Mar; 58(3):115–30.

Moseley AM Stark A, Cameron ID, Pollock A. Treadmill training and body weight support for walking after stroke. Cochrane Database Syst Rev. 2005 Oct 19 ;(4):CD002840.

Ng MF, Tong RK, Li LS. A pilot study of randomized clinical controlled trial of gait training in subacute stroke patients with partial body-weight support electromechanical gait trainer and functional electrical stimulation: six-month follow-up. Stroke. 2008 Jan; 39(1):154-60.

Page SJ, Szaflarski JP, Eliassen JC, Pan H, Cramer SC. Cortical plasticity following motor skill learning during mental practice in stroke. Neurorehabil Neural Repair. 2009 May; 23(4):382-8.

Pattichis CS, Elia AG. Autoregressive and cepstral analysis of motor unit action potentials. Med Eng Phys. 1999 Jun; 21(6):405–19.

Richards LG, Stewart KC, Woodbury ML, Senesac C, Cauraugh JH. Movement-dependent stroke recovery: a systematic review and meta-analysis of TMS and fMRI evidence.Neuropsychologia. 2008 Jan 15; 46(1):3-11.

Robinson RO, Herzog W, Bigg BM. Use of platform variables to quantify the effects of chiropractors manipulation on gait symmetry. J Manipulative Physiol Ther. 10:172-176, 1987.

Sharma N, Baron JC, Rowe JB. Motor imagery after stroke: relating outcome to motor network connectivity. Ann Neurol. 2009 Nov; 66(5):604-16.

Sabut SK, Lenka PK, Kumar R, Mahadevappa M. Effect of functional electrical stimulation on the effort and walking speed, surface electromyography activity, and metabolic responses in stroke subjects. J Electromyogr Kinesiol. 2010, doi:10.1016/j.jelekin.2010.07.003 (in press)

Stein RB, Everaert DG, Thompson AK, Chong SL, Whittaker M, Robertson J, Kuether G.Long-term therapeutic and orthotic effects of a foot drop stimulator on walking performance in progressive and nonprogressive neurological disorders. Neurorehabil Neural Repair. 2010 Feb; 24(2):152-67.

Stulen FB, De Luca CJ. Frequency parameters of the myoelectric signal as a measure of muscle conduction velocity. IEEE Trans Biomed Eng. 1981; BME-28:515–23.

Tong RK, Ng MF, Li LS, So EF. Gait training of patients after stroke using an electromechanical gait trainer combined with simultaneous functional electrical stimulation.Phys Ther. 2006 Sep; 86(9):1282-94.

Veg A, Popović DB. Walkaround: mobile balance support for therapy of walking. IEEE Trans Neural Syst Rehabil Eng. 2008 Jun; 16(3):264-9.

Visintin M, Barbeau H, Korner-Bitensky N, Mayo NE. A new approach to retrain gait in stroke patients through body weight support and treadmill stimulation. Stroke. 1998 Jun; 29(6):1122-8

Chapter 4

Conclusions

In this thesis we introduced a new therapeutic modality based on sensor-driven functional electrical stimulation (FET) for the recovery of walking in individuals with acute hemiplegia.We conducted very small randomized study in the acute phase of stroke and tested walking parameters and functional status of the patients with hemiplegia.

Our study shows that 4 weeks of FET therapy with the new sensor-driven electrical stimulation compared with conventional rehabilitation was beneficial.

The overall suggestion is that the ability to walk augmented with the timed stimulation of several muscles of the paretic leg is leading to an improved and faster recovery of walking.

All patients also reported favorable augmentation of voluntary effort to move the leg during walking. This suggests that the sensor-driven control is appropriate to assist in the walking motion. All patients also reported that they feel safer while being stimulated when walking compared to non-assisted walking. Patients suggested that this solution needs to be technologically improved in order to make the system more appealing for everyday use.

In the other part we used polymiography as a method to quantify the level of improvement by analyzing the level of muscle contribution and activation pattern. We examined single voluntary task/dorsiflexion and its execution, in 3 groups: FET, Control and Healthy.

We found that both groups of patients were successful in executing the task but the major difference was the way of the muscle activation. Our research showed that control of the required muscles was not inline within and between the groups.

The EMG envelopes and the coactivation coefficients showed that when electrical stimulation was applied in a manner that facilitated walking, it had positive effects on the recovery of voluntary control when compared to the same type of exercise but without.

- Overall findings suggest that facilitated exercise during the early phase of post-stroke recovery plays an important role in rehabilitation. This finding implies that new therapies need to include both task-oriented intensive exercise in order to provide input to the brain and augment the recalibration and reorganization of the preserved mechanisms and also a quantitative assessment of the changes to understand why the recovery occurred. This is important for clinicians and health care providers.

Our results presented are from a small studies and duration of treatment that was limited to four weeks, due to the typical length of stay in the rehabilitation unit. However, the results might be found of interest to others studying the physiological basis of recovery during rehabilitation.

The results from the ours and other research lead us to suggest that repetitive active movement mediated by electrical stimulation can enhance motor re learning following damage to the CNS.The term motor relearning is used to describe a set of process associated with prctise or experience leading to long term changes in the capability for movement.

Electrical stimulation is not the cure and the level of recovery depends very much on the impairment, type of stroke, time after the onset of stroke, and additional treatments provided to the patients. The best results are obtained in patients who exhibit some rudimentary functioning at the time of entering the problem. Electrical stimulation, improves the flexibility and range of the movement can be enhanced by other therapeutic methods, while the active range of movement is continually increased due to the strengthening of the muscles. It’s still uncertain if electrical stimulation contributes to the decrease of spasticity.

Electrical stimulation produces a better outcome when provided during the acute phase of stroke, compared to the chronic phase in which its application is prolonged and intensified. Consistent use contributes to a higher level of recovery and prevents the secondary loss of function which usually follows disuse.