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Hybrid Assistive Systems for Rehabilitation: Lessons Learned from Functional Electrical Therapy in Hemiplegics

Dejan B. Popović, *Member, IEEE*, Mirjana B. Popović

Abstract — **This paper suggests that the optimal method for promoting of the recovery of upper extremity function in hemiplegic individuals is the use of Hybrid Assistive Systems (HAS). The suggested HAS is a combination of stimulation of paralyzed distal segments (hand) in synchrony with robot controlled movements of proximal segments (upper arm and forearm). The use of HAS is envisioned as part of voluntary activation of preserved sensory-motor systems during task related exercise. This HAS design follows our results from Functional Electrical Therapy, Constraint Induced Movement Therapy, intensive exercise therapy, and use of robots for rehabilitation. The suggestion is also based on strong evidences that cortical plasticity is best promoted by task related exercise and patterned electrical stimulation.**

I. INTRODUCTION

PARALYSIS of the extremities is among the most debilitating injuries that the body can experience following a cerebro-vascular accident or degenerative process of aging. People with disability become dependent on other people or devices for even the simplest tasks.

Every year approximately 700,000 European citizens are affected by stroke, which is nearly one new disabled person per minute. The total number of individuals with hemiplegia in the European Union is estimated at 3.5 millions. Improving of the functioning is instrumental for augmenting of the impedance of disabled individuals.

Augmenting independence for a human, providing reintegration into society, and allowing him/her to be productive, will ultimately lead to improved quality of life.

II. ELECTRICAL STIMULATION FOR TREATING HEMIPLEGIC INDIVIDUALS

The use of electrical stimulation in rehabilitation of hemiplegic individuals was studied extensively during last 30 years. Kraft and colleagues [7] investigated improvement in the upper limb of chronic hemiplegic individuals who received one of two electrical stimulation treatments, conventional treatment, or no treatment. They compared four therapies applied for 3 months: EMG-initiated electrical stimulation of wrist extensors; low-intensity electrical stimulation of wrist extensors combined with voluntary contractions; proprioceptive neuromuscular facilitation (PNF); and no treatment. They used the Fugl-Meyer (FM) post-stroke motor recovery test and grip strength assessment. During the treatment, the FM scores of individuals receiving PNF improved 18%, low-intensity electrical stimulation improved 25%, and EMG initiated stimulation improved by 42%. The aggregate FM improvement of the treated groups was significant from the pretreatment to post-treatment, and the improvement was maintained at three-month and nine-month follow-ups (all $p < 0.005$). The treated individuals' improvement in grip strength was also maintained at both follow-ups ($p < 0.10$). In contrast, the non-treated group showed no significant change in FM scores or grip strength.

The influence of suprathreshold electrical stimulation of the *Extensor-* and *Flexor Carpi Radialis m.* on the biomechanical and functional movement parameters was compared with the effect of a standardized active repetitive training of the hand and fingers in 12 individuals [6]. Following a baseline phase that lasted between one and three weeks all of the individuals received electrical muscle stimulation for 20 minutes, twice daily. In a third phase the repetitive training of the hand and fingers was conducted for 20 minutes twice daily. Both interventions were applied in addition to conventional occupational therapy and physiotherapy. With the exception of spasticity in the hand and finger flexors, repetitive electrical muscle stimulation did not improve biomechanical or functional motor parameters of the centrally paretic hand and arm. The repetitive motor training, however, improved biomechanical and functional movement parameters significantly.

Feys *et al.* [4] in a single blinded, randomized, controlled multi-center trial followed 100 individuals that received sensorimotor stimulation or conventional treatment (control group) during 6 weeks. Individuals were evaluated by FM test, Action Research Arm test, and Barthel Index before, midway, and after the intervention period and at the follow-up 6 and 12 months. Individuals in the experimental group performed better on the FM test than those in the control group throughout the study period, but differences were significant only at the follow-up. Results on the Action

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DB Popović, is with SMI, Department for Health Science and Technology, Aalborg University, DK (phone: +45 96358726; fax: 45-98154008; e-mail: dbp@smi.auc.dk), and with Faculty of Electrical Engineering, University of Belgrade, SCG.

MB Popović is with Center for Sensory-Motor Interaction, Aalborg University, DK (phone: +45 96358758; fax: +45-98154008; e-mail: mpo@hst.aau.dk), with Faculty of Electrical Engineering, University of Belgrade and Center for Multidisciplinary Studies, Belgrade, Serbia.

Research Arm test and Barthel Index revealed no effect. The effect of the therapy was attributed to the repetitive stimulation of muscle activity. The treatment was most effective in individuals with a severe motor deficit.

Chae and Yu reported results from a study that included 28 individuals who received either neuromuscular stimulation or a placebo [3]. The neuromuscular stimulation was used to exercise wrist and finger extension one hour per day in 15 sessions. The control group received placebo stimulation over the paretic forearm. Outcomes included FM test and the self-care component of the Functional Independence Measure (FIM) at pretreatment, post-treatment, and 4 and 12 weeks post-treatment. Results revealed significantly greater gains in the FM scores for the treatment group after treatment, 4 weeks after treatment, and 12 weeks after treatment. FIM scores were not different between groups at any of the time periods ($p>0.10$).

Francisco *et al.* [5] assessed the efficacy of EMG-triggered neuromuscular stimulation in enhancing upper extremity motor and functional recovery of 9 acute hemiplegics. All of the individuals had a detectable EMG signal from the surface of the paretic *Extensor Carpi Radialis m.* and voluntary wrist extension. All of the individuals received two 30-minute sessions per day of wrist strengthening exercises with EMG-stim (experimental) or without (control) for the duration of their rehabilitation stay. Upper extremity FM test and the feeding, grooming, and upper body dressing items of the FIM were assessed at the time of the study entry and at discharge. Individuals treated with EMG-triggered stimulation exhibited significantly greater gains in FM and FIM scores compared with the controls.

Similar findings were reported by Cauraugh *et al.* [2], Powell *et al.* [15], and Tekeolu *et al.* [19].

Sonde *et al.* [16] studied the functional motor capacity of the paretic extremity when exposed to a low intensity, low frequency (1.7 Hz) transcutaneous electric nerve stimulation (low-TENS). Results showed that motor function increased significantly in the treatment group, compared with the controls. It was concluded that low-TENS could be a valuable complement to the typical training of arm and hand function in the rehabilitation of hemiplegic individuals.

III. INTENSIVE TASK RELATED EXERCISE FOR TREATING HEMIPLEGIC INDIVIDUALS

Sunderland *et al.* [17] followed the recovery of arm function after acute hemiplegia, and compared conventional physiotherapy with an enhanced therapy regime, which increased the amount of treatment. They also introduced behavioral methods to encourage motor learning. In a single-blind randomized trial, 132 consecutive hemiplegic individuals were assigned to two groups. Six months after the stroke the enhanced therapy group showed a small but statistically significant advantage in the recovery of strength, range and speed of movement. This effect seemed concentrated amongst those who had a milder initial impairment. The study does not provide answers as to why this improved recovery occurred and whether further development of this therapeutic approach might offer clinically significant gains for hemiplegic individuals.

The use of robot based devices to enhance therapy is proving that extensive exercise is beneficial.

MIT-Manus, a robot designed to provide interactive, goal-directed motor activity for clinical neurological applications was used to test whether the externally driven impaired limb influenced the motor recovery of individuals with hemiplegia. 20 hemiplegic individuals enrolled in a program supplemented by either robot-aided therapy or sham robot-aided therapy [1]. Impairment and disability declined in both groups between hospital admission and discharge. The robot-treated group showed a greater degree of improvement in all of the measures of motor recovery, and the change in motor status measured in the proximal upper limb musculature was significant. No adverse events resulted from robot-assisted therapy. In the continuation study, 56 hemiplegic individuals were randomly assigned either to receive robotic training (at least 25 hours) or exposure to the robotic device without training. Outcomes included the upper extremity component of the FM test, the Motor Status score, the Motor Power score, and FIM. By the end of treatment, the robot-trained group clearly demonstrated an improvement in motor outcome for the trained shoulder and elbow (Motor Power score, $p < 0.001$; Motor Status score, $p < 0.01$), which did not generalize an untrained wrist and hand. The robot-treated group also demonstrated a significantly improved functional outcome (FIM, $p < 0.01$).

A family of rehabilitation techniques, termed Constraint-Induced Movement Therapy (CIMT) has been developed [18]. The controlled experiments have shown that CIMT is effective in improving limb use in real-world environments after stroke. The therapy involves constraining movements of the less-affected arm with a sling for 90 percent of waking hours for 2 weeks, while intensively training the use of the more-affected arm. The common therapeutic factor in all CIMT therapy would appear to be inducing concentrated, repetitive practice utilizing the more-affected limb. Assessment of the effectiveness of CIMT was carried out on by Actual Amount of Use Test (AAUT), Motor Activity Log (MAL), Wolf Motor Function Test (WMFT), and Arm Motor Ability Test (AMAT) [8]. The results suggest a substantial improvement in the performance times of the laboratory tests and in the quality of movement (AMAT, WMFT and MAL), particularly in the use of the extremity in "real world" environments (AAUT). The effect sizes were large and comparable to those found in previous studies [18]. Miltner *et al.* [9] replicated the results of the CIMT and suggested significant improvement on a laboratory motor test and on a test assessing the amount of use of the affected extremity in daily routine activities in one’s life setting, with no decrement in performance at a 6-month follow-up.

IV. FUNCTIONAL ELECTRICAL THERAPY: USE OF NEURAL PROSTHESES INTEGRATED INTO INTENSIVE EXERCISE

Electrical stimulation of forearm and hand by a neural prosthesis in Functional Electrical Therapy (FET) enables hemiplegic individuals to grasp during the period when their hand is paralyzed; hence, prevent the disuse pattern. This added ability to grasp allows the users to voluntarily exercise their proximal muscles by accomplishing daily activities. The use of the more affected arm enhances the awareness regarding the ability to fulfill functional needs, and further promotes active extremity use. The functional sensory information generated by FET result in intensive brain training. Clinical, single blinded study that involved more than 60 hemiplegic individuals by Popović *et al.* analyzed the efficacy of the FET [10,13,14]. The individuals that participated in the study have been characterized as higher or lower functioning groups upon their ability to actively control the wrist and fingers when entering the study. The Higher Functioning Group (HFG) individuals could actively extend the more affected wrist for more than 20 degrees, and extend their MP and IP joints of all digits more than 10 degrees. Lower Functioning Group (LFG) individuals could extend the paretic wrist for 10 degrees only, and volitionally extend the MP and IP joints of the thumb and a minimum of two other digits for 10 degrees. The individuals were randomly assigned to participate in the FET or control groups. The FET group received conventional therapy and FET. FET was applied for three consecutive weeks for at least five days a week. The FET session consisted of 30-minutes of electrically assisted functional use of various objects (e.g., can, telephone receiver, comb, toothbrush, VCR tape). The grasping was externally assisted with the neural prostheses that used four channels of electrical stimulation (finger flexors and extensors, thumb flexors and extensors) [11,12]. The application of the neural prostheses resulted with a slowed down replica of the movement typical for able-bodied individuals when using simple objects. The individuals from the control group received conventional therapy only. The outcomes included: 1) Upper Extremity Functioning Test (UEFT), 2) Co-ordination of the arm joint movements, 3) Ashworth spasticity scale for key muscles of the upper extremities, and 4) Reduced Upper Extremity Motor Activity Log (RUE/MAL) at the point of entry to the trial, after therapy, and at 6, 13, 26 weeks [10,14].

This study confirmed that the enhanced use of the more affected arm is effective. Provision of the missing grasping from the beginning of the treatment accelerated the recovery and increased the level of functioning. The study also showed that FET resulted with carry over effects in the higher functioning group of hemiplegics. FET was forcing individuals to be actively involved in arm movement, while their grasp was assisted only.

The efficacy of FET can be attributed to several components. The applied stimulation activated synchronously several populations of motor (efferent) and sensory (afferent) nerve fibers. It may well be possible that some sensory pathways are activated optimally by relatively coarse stimulation. However, other effects may also contribute to increased control and function, such as the adequate sensory feedback that is generated by the actual performance of functional movements that cannot be performed without support. This also activates other sensory channels such as vision and the vestibular system and may additionally increase the awareness of the person of the availability and functioning of his/her affected arm. Another advantageous effect of applied stimulation is muscle training, resulting in stronger and more fatigue-resistant muscles. The over all suggestion from FET in individuals from the higher functioning group is that it greatly contributed to the recovery compared with no FET.

The use of FET in lower functioning group for only three weeks was not effective. The improvement in LFG of the arm/hand complex never reached the level that was good enough for daily activities; hence, a non-functional arm led to the later deterioration of function. We believe that the low recovery of the function in LFG was their inability to control proximal arm segments and move the hand. The FET can be expanded to control also the upper arm; yet, this is not practical because the control of upper arm (adduction/ abduction, humeral rotation, and flexion/extension) and forearm (elbow flexion/extension, pronation/supination) is very complex and require many stimulation channels and sensors for control which is not appropriate for clinical or home environment.

V. LESSONS LEARNED

Although most clinical studies were not large enough to produce statistically significant evidence, the over all conclusion is that active rehabilitation works better than passive. Most of the results agree that early management of disability leads to better recovery. Most of the researchers would agree that task related exercise is important. The results from basic studies suggest that the training of movement is contributing to the development of new representations in the cortical structures; thus, task related exercise could be understood as training of the brain. Since the brain organization favors what once learned and automated movement, the new movement strategies should be alike the one found in healthy individuals. The general finding is that hemiplegic individuals with higher level of functioning immediately after the stroke recover faster, reach a higher degree of recovery, and what is even more important respond positively to almost all treatments. On the contrary, the recovery for many hemiplegic individuals with high disability is slow, the reached functional level is below the required one for using of the paretic arm. The other finding is that many treatments are not suited well for hemiplegics with high level of disability (e.g., CIMT needs some level of functioning; otherwise, the hemiplegic individual would not be able to practice functional tasks. The FET needs some functions, since the electrical stimulation controls only distal muscle, that is, the wrist and hand). The use of robot assistants is certainly the major help in these cases; yet, the use of robots to assist grasping is beyond expectations at this time. The use of robots is linked to the treatment in the clinical environment.

VI. HEMIPLEGIC INDIVIDUALS WILL BENEFIT FROM THE REHABILITATION THAT APPLIES HAS

The conclusion from the above is that one should introduce to the present clinical practice of physical medicine for hemiplegic rehabilitation active movement, proprioceptive neuro-muscular facilitation, functional utilization of evolving synergies, and functional electrical stimulation of sensory-motor systems. The optimal method to do so is to combine several means of assistance (Fig. 1): robot driven manipulation of the arm and externally controlled grasping, possibly by use of HAS.

The HAS was introduced for the recovery of walking and standing in spinal cord injured individuals by Popović and Tomovic [20]. That HAS and the later versions aimed at distributing the assistance between the electrical stimulation of muscles during dynamic phases, and external skeleton during fatiguing static phases. The use of HAS in therapies of upper extremities is foreseen differently: the robot assistant operates as an orthosis (mechanical system that does not necessarily need to have anthropomorphic form) and comprises at least six degrees of freedom in order to allow positioning of the wrist and orientation of the hand during exercise, and electrical stimulation system to control grasping. In addition, the control that drives the robot needs to be adaptive and allow from complete external actuation to complete voluntary movement in the space.

This new HAS should have adaptive control that allows from complete control of positioning and orienting of the hand to complete control by the hemiplegic individual. The HAS is effective for prolonged external control of manipulation; yet also includes the needed electrical stimulation that is instrumental for training of the brain. The HAS will also provide hemiplegic individuals with the opportunity to “learn” movements by way of hours of repeated motor tasks.

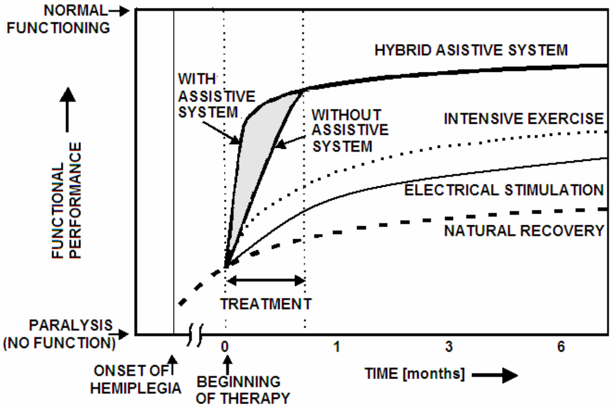

Fig. 1: The hypothesized therapeutic effects of therapies in hemiplegics. The sketched lines for different treatments follow results from clinical trials described in the paper. The assumed line for the effects of the HAS suggests that the recovery can be greatly increased compared to individual treatment.

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