Closed loop electrical muscle stimulation in spinal cord injured rehabilitation

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ABSTRACT: The effect of motor training using closed loop controlled Functional Electrical Stimulation (FES) on motor performance was studied in 5 spinal cord injured (SCI) volunteers. The subjects trained 2 to 3 times a week during 2 months on a newly developed rehabilitation robot (MotionMaker™). The FES induced muscle force could be adequately adjusted throughout the programmed exercises by the way of a closed loop control of the stimulation currents. The software of the MotionMaker™ allowed spasms to be detected accurately and managed in a way to prevent any harm to the SCI persons. Subjects with incomplete SCI reported an increased proprioceptive awareness for motion and were able to achieve a better voluntary activation of their leg muscles during controlled FES. At the end of the training, the voluntary force of the 4 incomplete SCI patients was found increased by 388% on their most affected leg and by 193% on the other leg. Active mobilisation with controlled FES seems to be effective in improving motor function in SCI persons by increasing the sensory input to neuronal circuits involved in motor control as well as by increasing muscle strength.

KEY WORDS: Rehabilitation robotics, functional electrical stimulation, closed-loop control, neural plasticity.

INTRODUCTION: Functional electrical stimulation (FES) mimics muscle action and afferent proprioceptive input of natural movements much better than passive exercise. However, during unimpaired voluntary motor action, muscle force is continuously adapted to the requirements; this is not the case for conventional FES. The Closed Loop Electrical Muscle Stimulation (CLEMS™) technology allows to adjust the FES in real time to the needs of the movement to be trained and to reproduce the kinematics and the dynamics of natural motor action. The ability of this technology to control the quadriceps torque during FES induced knee extension in healthy and paraplegic persons [1] as well as the total force output during a leg press movement in control subjects [2] has been shown previously. The aim of this investigation was to test the ability of this technology to control a leg press movement in paraplegic persons using a rehabilitation robot and to study the effect of controlled FES induced exercise on muscle force and spasticity.

MATERIAL AND METHODS: The MotionMaker™ is a new type of rehabilitation robot for the lower limbs combining two motorised hip-knee-ankle-foot orthoses equipped with position and torque sensors and a FES system (Figure 1). Its central control unit coordinates the orthoses and the FES to perform perfectly guided and controlled movements [2].

A CLEMS™ induced isokinetic leg press movement with a progressively increasing target force output was investigated during a 2 months exercise trial with 5 spinal cord injured (SCI) patients. Their neurological levels ranged from Th6 to Th12, 4 persons had an incomplete, 1 a complete paraplegia for more than 4 years. They exercised alternatively twice or three times a week for 1 hour. Spasticity was recorded before and after each work-out using the modified Ashworth scale [3]. The algorithms were fed by the position and force sensors integrated into the two orthoses. A specially developed mathematical model of the movement allowed to calculate continuously the torques setpoints for hip, knee and ankle joints to produce the desired total force output during the leg press movement. FES of the extensor (gluteus maximus, quadriceps and gastrocnemius) and flexor (hamstrings and tibialis anterior) muscles was continually adjusted through the algorithms taking into account measured and setpoint torques and muscle length.

RESULTS: The subjects adapted to the sensations produced by FES induced stimulation currents and muscle contractions within 2 to 4 weeks and maximal stimulation currents could then be used. FES induced spasms became infrequent. The spasm detection as well as the CLEMS™ algorithm accurately controlled spasms and output forces respectively.

Figure 2 presents an example of a leg extension (concentric work) followed by a leg flexion (eccentric work by the same muscles) with controlled FES in a complete Th12 SCI patient. The calculated target knee torques KTs, the measured knee torques KTm and the applied quadriceps stimulation current KSc for this movement are plotted in Figure 3. The biggest differences between the measured torque and the required torque are due to the limitation of the quadriceps stimulation current to 70mA for safety reasons. This explains the difference between the target horizontal force FXs and the measured force FXm. The algorithm shows its ability to control the force amplitude by forcing FXm close to FXs and the force direction by forcing FYm to zero. Three subjects with a marked hypertonia (3 - 4 on the modified Ashworth scale) saw their tonus decreased to 0 - 2 after one hour of exercise. The subjects with incomplete SCI noticed an increased awareness for muscle activity during electrically induced muscle contractions and were able to develop more voluntary strength with than without stimulation. At the end of the training, the electrostimulated force was fond increased by 397%. The voluntary force of the 4 incomplete SCI patients was improved by 388% on their most affected leg and by 193% on the other leg.

DISCUSSION: The increased electrostimulated muscle force might reflect increased fibre recruitment due to increased tolerance of stimulation currents as well as changes in contractile muscle properties. In incomplete paraplegics, increased sensory input to neuronal circuits involved in motor control might also contribute to an increased proprioceptive awareness and the improvement of voluntary muscle force. Functional changes within these circuits might bring about the effect of controlled FES on spasms and spasticity.

CONCLUSIONS: The CLEMS™ technology is able to control complex FES induced leg movements in paraplegic patients and opens new perspectives for motor rehabilitation. Induced exercise with controlled FES mimics normal voluntary muscle action quite closely compared to conventional FES exercise or passive mobilisation and might allow better motor relearning.

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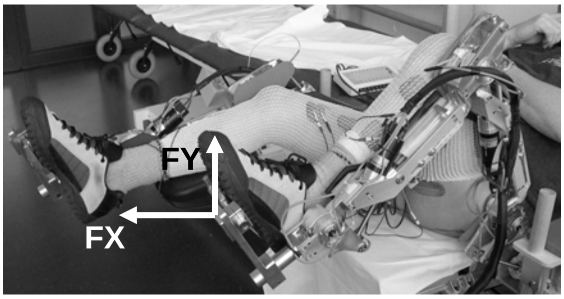
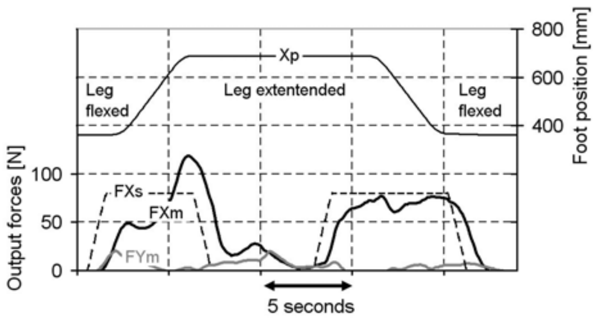


Figure 1: MotionMaker™ with an SCI patient and direction of forces, FX and FY.



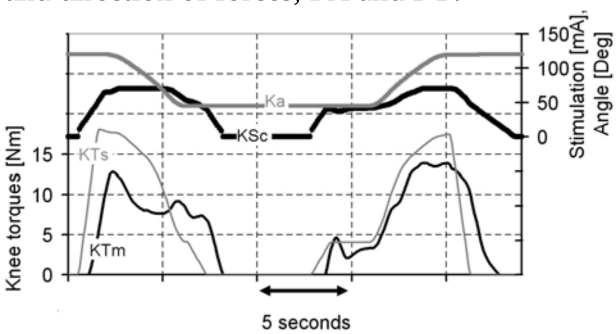


Figure 2: Extension (concentric work) and flexion (eccentric work) with foot position (Xp), horizontal force setpoint (FXs) and measured (FXm), vertical measured force (FYm), complete SCI subject.
Figure 3: Corresponding knee angle (Ka), knee torque setpoint (KTs) and measured (KTm) and quadriceps stimulation current (KSc), complete SCI subject

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