RAPID PROTOTYPING STATIONARY FES SYSTEM FOR WALKING AND GRASPING NEUROPROSTHESES

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ABSTRACT

A rapid prototyping FES system was developed that allows a modular implementation of walking and grasping neuroprostheses. Different sensor systems for the control of the neuroprostheses and different control strategies can be tested and tuned on the same system. This concept is more flexible compared to other FES systems that are built with a fixed set of sensors and a limited number of control strategies.

The rapid prototyping FES system consists of an eight channel constant current FES device for surface stimulation that is PC controllable, an eight channel data acquisition board and a closed-loop controller software programmed on a standard PC using LabVIEW. A graphical user interface allows a fast adjustment of all parameters, including the stimulation patterns, the sensor and controller settings. All parameters are stored in setup files and therefore allow a fast re-configuration of the neuroprosthesis to the individual subject's needs.

The rapid prototyping FES system was used to design individual grasping or walking neuroprostheses for 9 SCI and 2 stroke subjects. In a second phase the individual settings were transferred to a portable FES system.

INTRODUCTION

Several microprocessor or microcontroller FES stimulators have been developed to improve lower and upper limb functions in spinal cord injured (SCI) and stroke subjects [1-5]. Most of the proposed systems have a more or less fixed design and lack an open architecture. They generally operate with preprogrammed stimulation patterns for each stimulated muscle group that are stored in a look-up table. Often a single sensor combined with a control algorithm either triggers preprogrammed stimulation sequences or scales and reads the stimulation parameters out of a look-up table.

Contrary to the above described systems the rapid prototyping FES system has a very flexible and user friendly architecture. Stimulation systems with a variety of sensors and control strategies can be easily implemented. The shapes of the stimulation trains can be adjusted graphically. All the stimulation parameters are set up in graphical user interfaces (GUI) and are stored in setup files. Redundant multi-sensory systems can be evaluated and adapted individually to the subjects. A fully operational eight channel data acquisition system is integrated and allows to record all relevant stimulation data and measured sensor signals to a hard drive in real time. The acquired data are used to quantitatively evaluate the individual neuroprosthesis. The rapid prototyping FES system consists of three main parts:

- An eight channel constant current FES stimulation device
- An eight channel multifunction data acquisition board LabPC+ from National Instruments
- A closed loop controller implemented in LabVIEW with a GUI for walking and grasping neuroprostheses

FES STIMULATION DEVICE

The constant current FES stimulation device consists of a digital and 2 analog circuit boards. The digital circuit board receives the stimulation commands from a PC via the digital ports of the multifunction data acquisition card and generates the pulse control signals using a Motorola HC11 microcontroller. All signals from the PC are galvanically separated by HP2630 optocouplers. For safety reasons the stimulation device is battery driven.

On the analog circuit boards the stimulation pulses for 4 stimulation channels are generated from a single voltage controlled constant current controller and demultiplexed with bosfet switches. The stimulation current pulse form is composed of a positive rectangular current pulse with constant stimulation amplitude followed by a negative exponentially decreasing current pulse for charge balancing. The software for the HC11 microcontroller shown in figure 1 was written in assembler language.

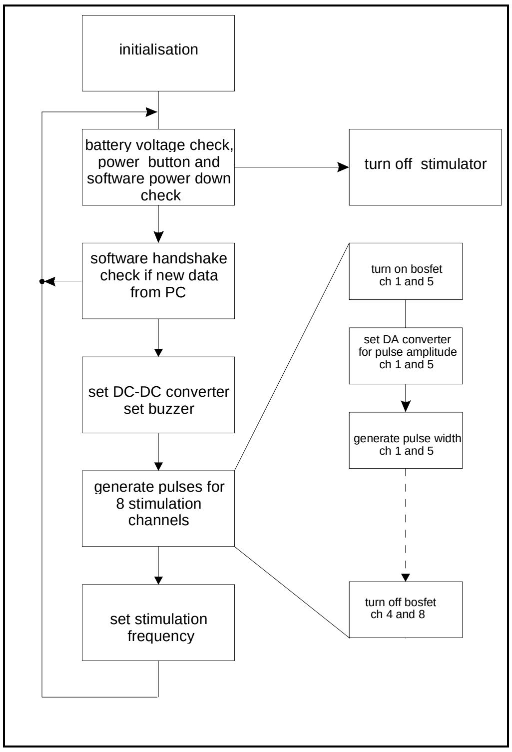

Figure 1: Flowchart of the HC11 assembler program

LABVIEW CONTROLLER SOFTWARE

The fast prototyping FES system was developed both for grasping and for walking neuroprostheses. There are major differences in the control schemes of walking or grasping FES systems. In walking systems the stimulation patterns are periodically triggered according to the recurrent gait cycles. Manually pressed push buttons or heel switches are commonly used to trigger the stimulation sequences [6]. Grasping is controlled more interactively. The subject wants to have control over the state of grasping at any time. Therefore two different control programs with easy-to-use GUI's had to be developed for walking and for grasping.

Prototype walking neuroprostheses software

The control software for the walking neuroprostheses consists 5 main sections: 1) a stimulation pattern generation and selection section; 2) a trigger definition section for different sensor types; 3) a programmable rule based controller; 4) a stimulation parameter definition section; 5) a data recording and a EMG amplifier setup section. This software was used to implement three different walking setups for incomplete SCI and stroke subjects.

Treadmill walking setup

In a first phase of the adaptation of a walking neuroprosthesis to a SCI or stroke subject the exact locations of the stimulation electrodes have to be found and adjusted in order to get the maximum out of the walking aid. For this FES assisted treadmill walking is a well established method. A recurrent, timed trigger starts the stimulation of the peroneal nerve in order to generate a flexion reflex that lifts the subject's leg with a complex step-like movement. With a delay of 250ms the tibialis anterior muscle is stimulated to correct the eversed foot position towards inverse position. Slow walkers can also benefit from the stimulation of the gastrocnemius muscle activated 50ms post triggering. Up to 8 stimulation channels can be combined in any desirable way.

Push button setup

In the push button setup the timed trigger is replaced by a push button. Whenever the push button is pressed a trigger is generated. The trigger activates the stimulation patterns. The push button control mode can be used either on the treadmill or during walking with crutches.

The subject has full control over his walking, but must press a push button to initiate every step.

Automatic heel off detection setup

In order to relieve the subject from pressing a push button to initiate every stride an automatic heel off detection setup was tested. Therefore three force sensitive resistors (FSR) were positioned under the heel, the 1st and the 5th metatarsal bone to detect reliably stance phase and heel off. The FSRs have in the unloaded swing phase a high resistance of several MΩ and with loading the sensor in stance phase the resistance decreases to 1.2kΩ when loaded with full body weight. The FSR's were connected to the analog inputs of the multifunction card in the same way as the push button described before. The pull-up resistors were 12kΩ.

Prototype grasping neuroprostheses

Compared to the walking controller software in the grasping controller software the rule based controller and the trigger section were replaced by a sensor signal processing section and a sensor information to muscle stimulation mapping section. Using these versatile software modules we implemented the following 4 control strategies.

1. Push button control

Whenever the push button is pressed the control variable of the grasping neuroprosthesis changes from 0 (neutral position) to 1 and the hand is opened by stimulating the finger extensors. The hand remains opened until the push button is pressed again. Then the control variable changes from 1 to -1 and the hand is closed by stimulating the finger and thumb flexors. The stimulated hand remains closed until the push button is pressed a third time. The fingers are opened and remain opened for 2 seconds to allow the subject to release the grasped object.

2. Slider control

An other simple control strategy is to use an analog sliding potentiometer to control the grasping activity. The sliding potentiometer works as a voltage divider and is supplied with 5 V. The slider sets the control variable between -1 for hand closing and 1 for hand opening. The neutral position 0 is in the middle of the sliding potentiometer at an output voltage of 2.5 V.

EMG control

Active EMG sensors (gain: 1400, high-pass cutoff freq.: 300 Hz, low-pass cutoff freq.: 4kHz) from Medicompex S.A. are used to control the grasping neuroprostheses with muscle activity of voluntary controllable muscles. A software routine eliminates the stimulation artifacts from the measured EMG signals by blanking the signals for 2ms after a stimulation pulse. The EMG signal then is rectified and low-pass filtered at 1.5 Hz.

3. Digital EMG Control

The grasping neuroprosthesis can be controlled using the preprocessed EMG signal from a voluntary controlled muscle like a Morse code. EMG activity which is higher than a predefined level is interpreted as active and levels below are interpreted as inactive. Short and long active phases can be distinguished. Two different EMG patterns are used to trigger grasping or releasing of an object. The finger flexors and extensors are controlled as described in the push button control mode.

4. Analog EMG control

In the analog EMG control mode the preprocessed EMG signals from two voluntary controllable muscles, e. g. the ventral and dorsal branch of the deltoid muscle, are used to control grasping. They are subtracted from each other to eliminate co-contraction. The resulting EMG activity proportionally sets the control variable and is treated in the same way as the output voltage of the sliding potentiometer. In the case where the two branches of the deltoid muscle are used to control grasping, a higher ventral activity results in a hand opening and a higher dorsal activity causes the neuroprosthesis to stimulate for hand closing.

RESULTS

The rapid prototyping FES system was used to design walking neuroprostheses for 3 incomplete SCI subjects and 2 stroke subjects. All subjects had a drop foot problem. In an early phase FES walking on a treadmill was used to find the right electrode positions and an appropriate sequencing of the flexion reflex stimulation and the stimulation of assistive muscle groups. The other stimulated muscles were the tibialis anterior muscle in order to correct an eversion of the foot and the gastrocnemius muscle to improve the walking speed of slow FES walkers. Fast FES walkers could not benefit from stimulation of the gastrocnemius muscle during lift off of the leg. In the beginning the subjects walked on the treadmill partially unloaded with a parachute harness. Later they could use crutches or a roller and walk freely. In a second phase FES treadmill walking with push button control was introduced to prepare the subjects for crutch walking. Three subjects also tried the heel off detection setup, that combined 3 FSRs with a rule based controller to trigger preprogrammed stimulation patterns. On the treadmill a reliability of 98% to detect the heel off phase at the right time was achieved.
Six tetraplegic SCI subjects used the system as a grasping neuroprosthesis. Their level of lesion varied ranged from C4 to C6. Two subjects were incomplete, but with severe grasping disabilities. The push button and the analog sliding potentiometer control were found to be more reliable and easier to implement by occupational therapists than the EMG control strategies. Although the EMG control strategies were more intuitive for the subjects to use they were more sensitive to artifacts occurring from unwanted activation of the controlling muscles while moving the arm, the upper body or during trunk stabilizing actions. The grasping capabilities with surface stimulation electrodes were surprisingly good once the stimulation points were located and marked. Although all subjects could significantly benefit from the grasping neuroprosthesis only the C4 and C5 SCI subjects decided to continue with a portable grasping system. These subjects had no passive hand function (tenodesis grasp) and therefore were only able to grasp an object with the help of FES.

CONCLUSION

The rapid prototyping FES system was a very useful tool to find the right configuration of a neuroprosthesis for a broad band of SCI and stroke individuals. With its open architecture and the capability to use all kind of sensor systems for man-machine interfacing the system was very flexible to adapt different neuroprostheses to the subjects and to find the best way how to control them. Very valuable were the graphical user interfaces that allowed a fast reconfiguration of all the system parameters. All parameters could be stored in setup files and reloaded in the next session. Once the subjects were satisfied the neuroprosthesis, it was implemented into a portable FES device. This approach allowed a fast adaptation of individual neuroprostheses. In addition, the data recording capability was a valuable tool for the validation of the performance of the neuroprostheses.

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