CLOSED-LOOP CONTROL OF AN FES SYSTEM INCORPORATING NATURAL SENSORY FEEDBACK USED FOR RESTORATION OF HAND GRASP IN TETRAPLEGICS

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ABSTRACT

A tetraplegic volunteer was implanted with an eight channel implantable stimulator to restore hand grasp function. He was also instrumented with a nerve cuff electrode around the cutaneous nerve innervating the radial aspect of the index finger. The nerve signal amplitude reflected mechanical events on the skin of the index finger. The activity from the natural sensors was used for automatic regulation of the stimulation intensities of the paralysed hand muscles. With the system in closed-loop control mode, the mean stimulation intensity to maintain a suitable lateral grasp could be significantly reduced compared to the stimulation intensity used by the subject in the open-loop control mode. We have shown the closed-loop FES system to function well on five separate days over a period of four months.

Keywords: electrical stimulation, cuff electrode, hand grasp, closed-loop control

INTRODUCTION

A spinal cord injury at the mid-cervical level results in a loss of sensory and motor function in both upper and lower extremities of the affected persons (tetraplegia). In order to restore basic hand function and enable tetraplegic individuals to grasp and manipulate objects hand neuroprostheses based on Functional Electrical Stimulation (FES) have been developed [Buckett et al., 1988; Kilgore et al., 1989]. These systems usually control the grasp without any grasp specific feedback information such as finger position or grasp force (open-loop systems). Due to lack of sensation in the hand, the tetraplegic person must rely on vision and experience to estimate the required grasp force when picking up objects. The object weight, fragility, and surface texture must be considered when adjusting the grasp force. In addition, the required grasp force varies when the hand is moved or when the muscles are fatigued. Consequently, persons with hand neuroprostheses tend to apply a larger grasp force than may actually be required for a given task [Riso, 1997].

In order to compensate for the sensory information deficit of the tetraplegic person we use the signals from natural sensors already present in the skin of the fingertips to control the electrical stimulation of the muscles incorporated in the hand grasp. These cutaneous mechanoreceptors respond to mechanical events on the skin such as changes in contact force, skin stretch, and slips across the skin. Mechanoreceptors are usually not affected by the spinal cord injury. It has been shown that these natural sensors have the potential to provide useful feedback information that may be used to improve the control of hand grasp neuroprostheses [Haugland and Lickel, 1998].

This paper presents the implementation of nerve signals recorded with a cuff electrode as a feedback signal to control hand grasp with an implantable muscle stimulator. We evaluated the hand grasp system during a simulated eating task in order to show the achieved improvement by using closed-loop control.

MATERIALS AND METHODS

A 28 year old male C6 level tetraplegic volunteer was implanted with a tripolar nerve cuff electrode around the cutaneous nerve innervating the radial aspect of the index finger. He was also instrumented with a commercially available eight-channel muscle stimulator to restore hand grasp, which is a part of the Freehand System (NeuroControl Corp., Cleveland, Ohio, USA). Both the nerve cuff electrode and the epimysial stimulation electrodes were implanted in the subject´s left hand and forearm. Informed consent was obtained from the subject, and the implantations were approved by the local ethics committee.

The implanted stimulator was controlled with a custom-made transmitter via a radio-frequency link that also provided power for the implanted circuitry. This external device was controlled via the parallel port of a PC and mimicked the function of the external control unit of the Freehand System based on the protocol described in [Smith et al., 1987].

The muscles were stimulated at 20 Hz and pulse width modulation was used to control the stimulation intensity. To be able to control individual muscles incorporated in the hand grasp with a single command signal, a template for a lateral grasp (key grip) was generated using six different muscles located in the hand and the forearm of the subject [Kilgore et al., 1989]. Fig. 1 shows the hand grasp template along with the corresponding lateral pinch force. The command signal ranged from 0 to 100, corresponding to fully open hand (0) and fully closed hand (100) respectively. The pulse widths for each muscle were determined using the command signal and the grasp template and then sent to the implanted stimulator via the radio-frequency link.

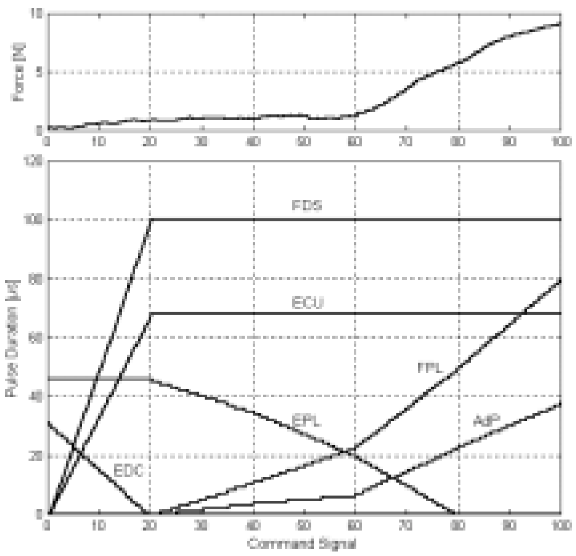

Fig. 1: Hand grasp template and lateral pinch force. Abbreviations: EPL, extensor pollicis longus; EDC, extensor digitorum communis; ECU, extensor carpi ulnaris; FDS, flexor digitorum superficialis; FPL, flexor pollicis longus; AdP, adductor pollicis.

The subject could control opening and closing of the hand with two buttons mounted on the headrest of his wheelchair. One button was used to switch the system on and ramp the command signal up and the other button was used to ramp the command signal down and switch the system off.

The nerve signal recorded with the cuff electrode was amplified 10,000 times with a battery powered, transformer coupled, low-noise pre-amplifier (Micro Probe Inc., ADT-1) and passed through an isolation amplifier (Burr-Brown, ISO220). This signal was then bandpass filtered between 1 kHz and 4 kHz and amplified by a factor of 10 with an analogue fourth-order filter (Krohn Hite, model 3750). The filtering reduced EMG contamination and enhanced the signal to noise ratio of the recorded nerve signal. The resulting signal was then sampled at 10 kHz, digitally rectified and integrated in blocks of samples from each stimulation pulse interval (bin-integration) with a PC-controlled digital signal processor (Texas Instruments, TMS 320C25).

The rectified and bin-integrated signal (RBI-ENG) was further processed with a first order autoregressive filter in order to remove interference from slow changes in background activity, smooth the signal, and enhance peaks [Haugland and Hoffer, 1994]. Detection of mechanical events on the skin of the index finger that resulted in a variation in the amplitude of the nerve signal was done by comparing the processed nerve signal to a fixed threshold level.

Every time the processed nerve signal was higher than the threshold level, the command signal was increased to 100 for the next stimulation cycle (i.e. next stimulation pulse for each of the incorporated muscles), which also was at twice the instantaneous stimulation frequency. After this initial reaction the command signal was set to a higher level than before the event, linearly depending on the amplitude of the processed nerve signal. In periods when no events where detected in the nerve signal the command signal was automatically decreased using a slow linear ramp.

A simulated eating task was used to evaluate the system. The subject held a fork in a lateral grasp. He was then asked to scoop three small "pancakes" made of modelling clay (mass = 5 g, diameter = 3 cm) from a plate, take them to the mouth, and then put them back on the plate. This was repeated three times with breaks of 10 seconds in between resting his hand on the table. The timing of the task and the number of objects were chosen based on a video analysis of several meals while the subject was eating in a social environment with the system in closed-loop control mode.

RESULTS

Fig. 2 shows a typical example of the performance of the system in a simulated eating task. In order to pick up the fork the subject turned the system on causing the hand to open. He then placed the fork in the hand and increased the command signal to 100 using one of the control buttons mounted on the headrest of his wheelchair. The system then used the processed nerve signal for automatic regulation of the stimulation intensities of the paralysed hand muscles. An adequate grasp force was therefore maintained all the time without any need for the subject to further interact with the system. During the resting phases, the system would keep decreasing the command signal resulting in opening of the hand. Because of the orientation of the hand, the fork would lie horizontally on top of the index finger. However, when the hand was moved it could not be closed fast enough to catch the fork. To avoid this situation we allowed the command signal only to decrease to a minimum level, where the fork was kept in the grasp, but with a minimum of applied force (see Fig. 1). When an event was detected in the processed nerve signal the command signal was automatically increased in order to maintain a stable and secure grasp. At the end of the eating task the subject ramped down the command signal with one of the control buttons and then switched the system off.

Using the system in open-loop control mode our subject usually turned the command signal up to 100 to be certain he maintained a stable grasp. He kept this level until he released the fork. The command signal, averaged over the whole task, was about 20 % less in closed-loop control mode compared with that in the open-loop control mode with a command signal level of 100. This means that the mean lateral pinch force could be reduced by 40 % (see Fig. 1). Using less force allowed the subject to perform tasks longer due to a delayed onset of muscle fatigue.

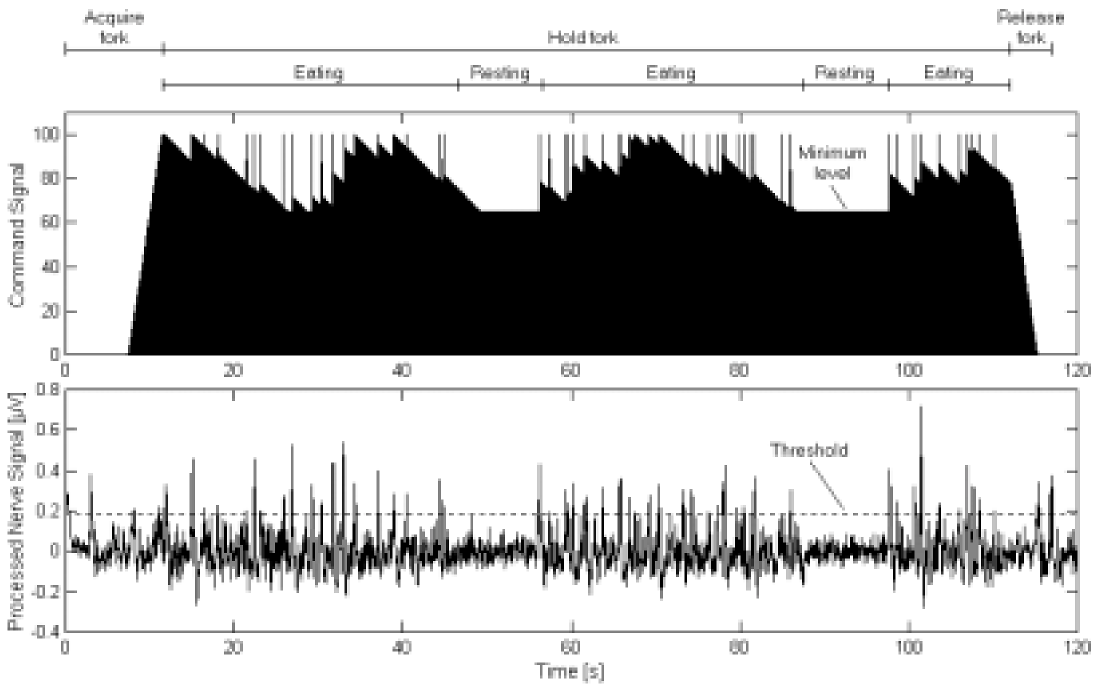

Fig. 2: Processed nerve signal and resulting command signal for a simulated eating task. When the processed nerve signal was higher than the threshold, a catch reaction was initiated and the command signal was increased afterwards depending on the amplitude of the processed nerve signal after detection.

CONCLUSION

We have shown the closed-loop FES system to function well on five separate days over a period of four months. With the system in closed-loop mode, the mean stimulation intensity to maintain a suitable lateral grasp for an eating task could be significantly reduced compared to the stimulation intensity used by our subject in the open-loop control mode.

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