IMPROVEMENT OF THE CATCH REACTION OF A CLOSED-LOOP FES HAND GRASP NEUROPROSTHESIS

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Abstract

Functional electrical stimulation of paralyzed hands can provide tetraplegic individuals with basic hand function. To improve the control of electrically stimulated hand muscles we used signals from natural cutaneous sensors recorded with a nerve cuff electrode implanted around the palmar digital nerve innervating the index finger. Events on the skin, such as changes in contact force, skin stretch, and slips across the skin, could be detected in the nerve signal and were used as feedback information for the stimulation system. A method is presented for improving the system reaction when such events on the skin occur. The proposed method used one to three pulses with maximum pulse width applied with twice the instantaneous stimulation frequency. The results suggest that using one maximum pulse provides the best system reaction with minimum stimulation effort.

Introduction

Several FES hand grasp systems were developed in the past decade [1-4]. These systems usually control the grasp without any grasp-specific feedback information, so that the user has to rely on vision and experience to perform grasping safely. At the Center for Sensory-Motor Interaction a new technique of providing such systems with feedback information was developed by incorporating signals from natural sensors in the skin of the index finger recorded with a nerve cuff electrode [5].

The signals from the natural sensors were used to provide a hand grasp neuroprosthesis with a 'catch reaction' to prevent objects from slipping out of the grasp. Every time the nerve signal crossed a predefined threshold level, the system reacted with an increase of stimulation intensity of the muscles involved in the grasp. After this initial reaction, the stimulation intensity was decreased with a slow linear ramp to minimize the grasp force.

In this study we investigated the effect of applying a number of maximum pulses (i.e., pulses with maximum pulse width) with twice the instantaneous stimulation frequency, to catch a slipping object. The hypothesis was that a higher number of applied maximum pulses leads to a higher maximum force of the catch reaction and to a higher rate of grasp force increase. A decrease of the system reaction time was also expected.

Materials and Method

A 28-year-old male C5 level tetraplegic volunteer was implanted with a tri-polar nerve cuff electrode around the palmar digital nerve innervating the radial aspect of the index finger [5]. 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 volunteer's left hand and forearm. Informed consent was obtained from the volunteer, and the local ethics committee approved the implantations.

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 involved 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 volunteer [6]. The command signal ranged from zero 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 a radio-frequency link.

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 (1 kHz to 4 kHz) and further amplified by a factor of 10 with an analogue filter (Krohn Hite, model 3750). The resulting signal was 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 was further processed to remove interference from background activity and to enhance peaks in the signal [7]. Mechanical events on the skin of the index finger resulted in a variation in the amplitude of the nerve signal. Detection of these events was done by comparing the processed nerve signal to a fixed threshold level.

The tetraplegic volunteer was seated next to a table with his instrumented left arm placed on the table. The lower left arm was placed in a vacuum cast, providing support for elbow, wrist, and the fingers from the 5th to the medial half of the 2nd finger (see Fig. 1). A grasp force transducer instrumented with strain gages was placed between the thumb and the flexed index finger. Two rectangular plates (70 x 70 mm) were mounted on the grasp force transducer. The surface of the plates was covered with suede. The design of the grasp force sensor and the placement of the strain gages were optimized to minimize the error caused by applying force on different places of the plate area. A torque motor with a 10 cm lever arm was used to apply a constant pull force of 1.8 N at the end of a string attached to the grasp force transducer. The pull force was measured with an in-line pull force transducer based on strain gages. The movement of the motor lever arm (i.e., the movement of the grasp force transducer in the hand) was measured with a high-resolution, low-friction, linear potentiometer.

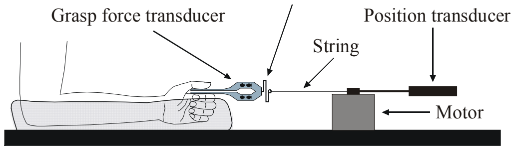

Fig. 1: Slip experiment set-up

Every time the processed nerve signal (ProcENG in Fig. 2) crossed a predefined threshold level, indicating a slip of the grasp force transducer, the system applied a catch reaction to stop the object from slipping out of the grasp. Applying one, two or three maximum pulses (i.e., an increase of the command signal to 100) with twice the instantaneous stimulation frequency was tested. After this initial reaction, the command signal was set to a level 10 points higher than before the reaction. In periods were no events where detected in the nerve signal the command signal was automatically decreased using a slow linear ramp of six points per second.

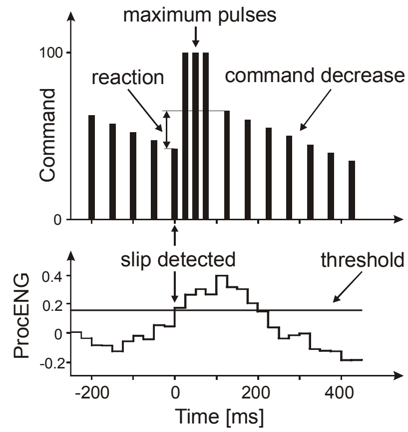

Fig. 2: Catch reaction of the hand grasp neuroprosthesis

Results

Experiments were conducted to investigate if the system was able to react to and stop a slip. A large number of slips (114) was produced. This was done by having the stimulated hand of the tetraplegic volunteer holding the object and decreasing the command signal with a slow linear ramp until the grasp force was too small to hold the object.

Each time a slip was detected the system reacted correspondingly with one of the tested catch reactions (i.e., different number of maximum pulses). The original system was also tested, using no maximum pulse and only increasing the command signal with a fixed amount with twice the instantaneous stimulation frequency.

Fig. 3A shows the effect of the number of applied maximum pulses on the maximum force of the catch reaction, defined as the maximum grasp force increase in a 250 ms window after detection. The measurements suggest a linear relationship between the maximum force increase and the number of maximum pulses.

Fig. 3B shows the effect of the number of applied maximum pulses on the maximum rate of grasp force increase of the catch reaction. The rate of grasp force increase was very low when no maximum pulses were applied and was clearly higher when one to three maximum pulses were applied.

Fig. 3C shows the effect of the number of applied maximum pulses on the system reaction time, defined as the time from detection of an increase in the processed nerve signal to the time the grasp force was 5 % higher than at the time of detection. Applying any number of maximum pulses led to a decrease in the system reaction time, whereas the number of applied pulses had no further influence on the system reaction time.

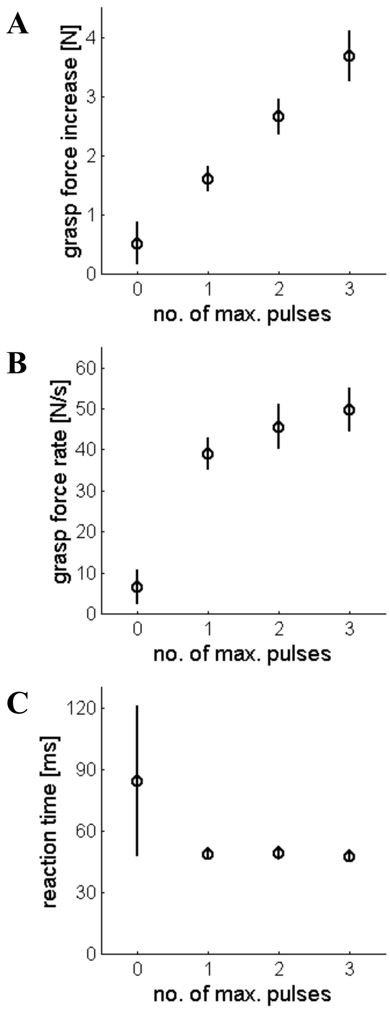

Fig. 3: Effect of the number of maximum pulses on the maximum grasp force increase (A), on the maximum rate of grasp force increase (B), and on the system reaction time (C). Results are expressed as mean values with the bars indicating the standard deviation.

Discussion and Conclusion

We investigated in a laboratory-based experiment set-up the use of maximum pulses as the catch reaction of a closed-loop hand grasp neuroprosthesis incorporating natural sensors. A tetraplegic volunteer was instrumented with a Freehand™ implant and implanted with a nerve cuff electrode around the palmar digital nerve innervating the radial aspect of the index finger. He was holding a flat object in lateral hand grasp. The object was pulled with a constant force of 1.8 N. Decreasing the stimulation intensity with a slow linear ramp produced slips of the held object that were reflected as peaks in the recorded nerve signal. The system reacted to every occurring slip by applying a number of maximum pulses with twice the instantaneous stimulation frequency. The stimulation intensity was then set to a higher level than before the reaction. This catch reaction should stop the slipping object fast and with minimum stimulation effort to prevent early fatigue of the stimulated muscles.

The effect of the number of maximum pulses on the maximum grasp force increase, on the maximum rate of grasp force increase, and on the system reaction time were investigated. A higher number of maximum pulses led to a higher maximum force increase. The maximum force rate was clearly increased and the system reaction time was clearly decreased by applying one maximum pulse compared to applying no maximum pulse. Any further addition of maximum pulses showed only small differences, but increased the stimulation effort. A short reaction time and a high force rate were important to stop a slip. Hence, using one maximum pulse provided the best compromise between improvement of the catch reaction and minimum stimulation effort.

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Acknowledgements

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