Development of a Feedback-Controlled Hand Neuroprosthesis: FES-Supported Mirror Training

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Introduction

Functional Electrical Stimulation (FES) is a widely used technique for physical rehabilitation of patients after stroke or spinal cord injury. Several neuroprostheses have been proposed for restoring or improving grasping function in patients [1]. Most of those systems are open-loop: they apply fixed stimulation patterns with predetermined intensities at discrete time events. Adaption towards the time-variant, individual response and the patient's intention is missing. We introduce a new feedback-controlled hand neuroprosthesis that enables a real-time adjustment of stimulation parameters and virtual electrode positions depending on the patient's behavior. In the following, the components of the system are described in detail and its benefits for an enhanced mirror training are outlined.

Components of the Hand Neuroprosthesis

Stimulator

Our neuroprosthesis utilizes the recently introduced RehaMovePro stimulator (Hasomed GmbH, Germany) with science adapter and demultiplexer [2]. The system supports electrode arrays with up to 61 elements and configuration updates for every applied stimulation waveform. Electromyography (EMG) measurements are facilitated from separate surface EMG electrodes or via the active stimulation electrodes. This feature reduces the hardware setup and supports intention recognition (volitional EMG).

Electrode Arrays

Electrode arrays help to overcome some of the disadvantages of standard surface electrodes such as long placement times and static electrode positions [3]. They consist of multiple, small elements that can be activated separately. Virtual electrodes can be formed by any combination of those elements. In our setup with the RehaMovePro, virtual electrodes can be dynamically changed in position and size. In collaboration with physicians and therapists, we designed two electrode arrays: one with 35 elements to be placed above the wrist and finger extensor muscles (cf. Fig. 1), and one with 24 elements to be placed above the finger flexor muscles. The customized arrays are manufactured from flexible printed circuit boards.

Sensor System

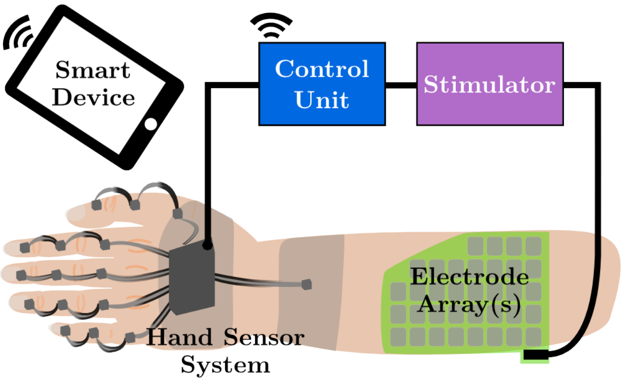

Fig. 1: Schematic illustration of the hand neuroprosthesis.

In a feedback-controlled neuroprosthesis, we need to measure the stimulation outcome in real-time. For clinical practice, it is beneficial if the system is portable and its setup is quick. Therefore, we developed a new hand sensor system based on inertial measurement units (IMUs). Each finger can be provided with a sensor strip that includes three IMUs, one placed on each segment as seen in Fig. 1. We use 9-axis sensors, each of which combines a 3-axis gyroscope, a 3-axis accelerometer, and a 3-axis magnetometer (MPU-9250, InvenSens Inc., CA, USA). On the back of the hand, a central microcontroller-based processing unit is placed with an additional IMU (cf. Fig. 1). Orientations of the sensors are estimated and joint angles between two sensors are evaluated. Our IMU hand sensor system allows to track hand movements, even if they are complex or non-natural. Additionally, commercially available IMUs as well as the optical measurement system Leap Motion are utilized, e. g. to track the arm movement or the hand postures of the non-paralyzed hand.

Control Unit

The (control) algorithms are initially developed in Matlab/Simulink on a regular PC using Linux Target for Simulink Embedded Coder (The Mathworks Inc, MA, USA). For the clinical environment, they are then transferred to a miniaturized computer and the communication with the user is realized via a smart device application (cf. Fig. 1).

Example: FES Supported Mirror Training

Mirror training (MT) is a therapeutic approach in patients with hemiplegia, such as stroke survivors, to facilitate motor recovery of the lower and upper limbs. Via a mirror placed in between the two limbs, the illusion of two synchronously moving healthy limbs is achieved. Studies showed that the perception of the apparently recovered, paralyzed limb can promote its functional recovery [4].

The combination of MT and FES on the paralyzed limb has been suggested to encourage greater gains of the interventions while requiring less time. The visual biofeedback is extended by tactile perception and proprioception. Recent studies in hand and arm rehabilitation combined MT and FES using fixed stimulation patterns [5], or synchronization via a switch at the healthy hand or EMG thresholds [6]. They found increased motor recovery in terms of medical scores in patients who received the combined treatment in comparison to a control group. Major drawbacks of those studies were the poor synchronization of FES and MT as well as the reduction to a single stimulated movement (fixed stimulation position(s)).

We utilized our hand neuroprosthesis in an FES supported MT which enables the stimulation of several movements and synchronizes the FES to the movement of the healthy hand via wireless motion tracking. Four different movements were defined for training of the hand extensors: (1) ulnar wrist extension, (2) straight wrist extension, (3) radial wrist extension, and (4) rest position (flexion, no stimulation). For each of the movements (1)–(3), an individual virtual stimulation electrode was defined in the array, which was placed over the extensor muscles in the forearm. The therapist manipulated the stimulation position via a graphical user interface and saved satisfying positions for each movement. The approach was tested with a reduced setup: the IMU hand sensor system was substituted by two wireless inertial sensors (RehaGait, Hasomed GmbH, Germany), which were placed on the forearm and on the back of the paralyzed hand. They were used to track the wrist extension angle and the wrist abduction angle. The mirror was omitted, as the experiments were conducted with three healthy participants.

After the setup of the system (donning, calibration, identification of stimulation positions), the volunteers were able to control the applied FES by performing the defined movements (1)–(4) with the opposite hand as seen in Fig. 2. The rest position did not involve stimulation and therefore enabled the participants to take breaks. A continuous transition between movements was possible: the virtual electrode in the array was moved automatically and in real-time to the position assigned to the detected movement. The stimulation intensity was increased until the wrist angles of both hands were the same or until a previously set, individual tolerance level was reached. In summary, our system promoted a variety of synchronous movements of the hands and left the control to the participant.

Conclusion

We presented a new adaptive hand neuroprosthesis design that facilitates feedback-control of FES, the generation of various hand movements, and biofeedback. It enables clinicians and patients to explore new therapeutic strategies which incorporate individual adaption to the patient and the patient's intention. The combination of mirror training and FES via electrode arrays and its synchronization via motion tracking demonstrated the usefulness of our concept. This approach will be further investigated and extended in the near future.

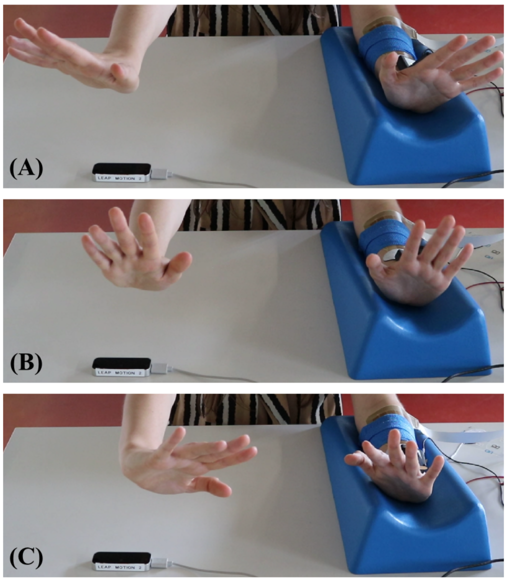

Fig. 2: Three different hand postures could be controlled within the FES supported mirror training: (A) ulnar wrist extension, (B) straight wrist extension, and (C) radial wrist extension. In this example, the participant's left hand was moved only by FES that was controlled by the right hand.

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