INTFES: A multi-pad electrode system for selective transcutaneous electrical muscle stimulation

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Abstract

In recent years, the use of multi-pad electrodes for transcutaneous electrical muscle stimulation has been suggested to achieve a better selectivity of muscle control. Here, we present INTFES – a device for multi-channel functional electrical stimulation via an array of electrodes. The basic design characteristics of the device are presented and a number of clinical studies that show its functional advantages over classical single-electrode stimulation are discussed.

***Keywords**: multi-pad electrodes, selective muscle stimulation, FES.*

Introduction

Transcutaneous electrical muscle stimulation is concerned with the elicitation of muscle contractions via electrical impulses delivered through electrodes placed on the skin. Electrical stimulation of muscles can be a functional tool for patients with motor dysfunctions (e.g. after spinal cord injury or stroke) [1]. While originally electrical muscle stimulation targeted mainly function compensation, today, it is mostly envisioned for therapy [2]. One major challenge in electrical muscle stimulation is the achievement of selective muscle activation as electrical currents tend to spread – in addition to the desired motor nerve – over many other motor nerves that should actually not be activated [3]. An additional difficulty comes from the fact that the ideal position for stimulation varies substantially from one individual to the next [4,5]. Thus a major factor to achieve good selectivity involves the proper placement and geometry of electrodes [6]. In the last years, the usage of multi-pad electrodes has been suggested to achieve a better selectivity during stimulation [7]. The basic idea for the use of such array electrodes is illustrated in Fig. 1 for the control of finger and wrist movement. Here, a whole array of electrodes is placed on the forearm. Based on the specific muscle activation (e.g. flexion of index finger), specific array elements of the electrode are activated. Based on this basic idea, we present INTFES – a device for multi-channel functional electrical stimulation via an array of electrodes. First, the basic characteristics of the device are described. Next, experiments and studies performed so far are discussed. Finally, the use of INTFES in the publicly funded research project HYPER is outlined.

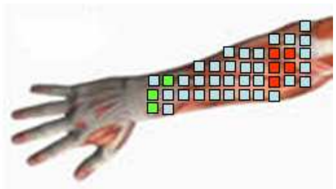

Fig. 1: Basic principle behind the use of multi-pad electrodes.

The INTFES Device

In Fig. 2, a picture of the INTFES device is shown. INTFES is a single channel electronic stimulator for Functional Electrical Therapy (FET). The two main components of INTFES are the stimulator and the array electrodes consisting of 16 self-adhesive pads and including a stimulation channel multiplexer board. The multi-pad electrodes depicted here are envisioned for placement on the forearm for the control of wrist and finger function. Other electrode geometries are used for other body locations. Via the multiplexer, up to 16 fields of an INTFES electrode can be activated asynchronously. Up to two 16-pad electrodes can be attached to the INTFES stimulator concurrently. The parameters of the biphasic charge compensated constant current impulses delivered to the pads can be adjusted in the following ranges: stimulation current (0–50mA), stimulation frequency (1–50 pulses per second), pulse duration (50–1000µs); INTFES can be fully controlled by a host computer (PC) via a Bluetooth communication link. Furthermore, in a manual adjustment mode, the device can be controlled directly without the necessity of a PC.

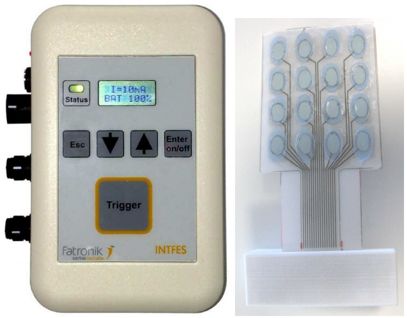

Fig. 2: INTFES device. Left: Stimulator. Right: Array electrode with 16 pads.

Experiments and Results

In the course of development of INTFES, a range of experiments have been performed. These served (1) to determine important design characteristics of INTFES, (2) to show the advantage of selective and multi-pad stimulation over classical single-electrode stimulation, and (3) to develop methods for automatically finding the optimal position, size, and shape of a “virtual electrode” resulting from the selective activation of particular pads.

Design Characteristics

Concerning the design characteristics, a first group of studies investigated the influence of (1) the gap size between array elements, (2) the resistivity of the electrode-skin material, and (3) the position of the cathode and anode on (a) the electrical field distribution, (b) the current density distribution, and (c) the current loss (being correlated with pain perception) [8,9]. The methods used for this purpose were simulations with finite element and nerve models and measurements on a pig abdomen. Results in [8] showed that when using a continuous gel sheet for all pads, the gel resistivity should be adapted depending on the gap size in order to achieve a good tradeoff between a uniform and a selective activation. For setups in which anode and cathode are connected through a gel layer it was found that gel resistivity should be higher than 50Ωm and that the distance between anode and cathode should be at least 19mm.

Functional Advantages of Electrode Arrays

Different aspects of the functional advantage of multi-pad electrodes in comparison to common single-pad electrodes were demonstrated in both healthy subjects and different patient populations.

A crucial function needing selective muscle control is the grasping function. In [3] it was shown how to reconstruct hand opening and closing for palmar and lateral grasps of individuals with chronic tetraplegia based on grasp patterns of healthy subjects using multi-pad electrodes. The optimal electrode-pad configuration varied significantly from subject to subject.

Another study [10] showed the importance of selectivity achieved by multi-pad surface electrodes for the reduction of wrist tremor in individuals with Parkinson’s disease or essential tremor.

In [11], the advantages of multi-pad electrodes for providing selective correction of drop-foot in hemiplegic individuals were shown. For this purpose, the matrix electrode was positioned over the peroneal nerve and primary dorsiflexor muscles. There was found a very high sensitivity to the position, size, and shape of the virtual electrode when stimulating over the nerve. This indicates that the use of configurable multi-pad electrodes is favorable compared with conventional electrodes.

Further experiments were made concerning muscle fatigue in patients with chronic spinal cord injury [12]. It was demonstrated that a 4-pad electrode setup on the upper leg with alternating activations led to significantly less muscle fatigue of the quadriceps muscle than a one-pad electrode setup.

Automatic Selection of Pad-Configuration

As indicated above, the use of multi-pad electrodes is an important tool to achieve optimal selectivity of muscle control, particularly as optimal position and shape of the virtual multi-pad electrode varies substantially from individual to individual. To reduce the configuration effort, it is thus desirable to develop methods to automatically determine the optimal configuration for a particular subject. This issue has been addressed in a number of publications.

In [13], the optimal virtual electrode shape for hand opening and closing in patients with spinal cord injury was obtained by comparing the FES induced grasp function with the one of healthy individuals. For this purpose, different finger and wrist joint angles were recorded from goniometers and their aggregate error was calculated. The optimal electrode shape was the one resulting in a minimal error.

In [5,14], another method for optimizing spatial selectivity of multi-pad electrodes was presented. For this purpose, individual muscle twitches were measured via a single accelerometer positioned on the dorsal side of the hand while stimulating with different electrode configurations. It was shown that induced wrist or finger flexion/extension produce different, characteristic wave shapes of acceleration. This information was used to feed an artificial neural network for detecting correlations of each pad and muscle activation. This resulted in a configuration procedure to determine optimal pad selections for particular desired movements.

A further method for automatic detection of optimal contact with a multi-pad surface electrode for reduction of wrist tremor was introduced in [10] based on a custom designed program that determines the position on the skin that is closest to the flexor/extensor muscle motor point.

INTFES and the Project HYPER

INTFES allows for selective and efficient electrical muscle simulation. Such characteristics are an important requirement for the objectives targeted in the project HYPER[1]. This multi-center 5-year research project is financed by the Spanish Government and is aiming at developing a robotic device consisting of a neurorobotic and a neuroprosthetic (FES) part for motor function compensation and restoration in subjects with spinal cord injury, cerebral palsy, and stroke. For the neurorobotic part, a special exoskeleton for the lower and upper limbs is being developed. For the neuroprosthetic part, the INTFES device will be applied in different configurations. The HYPER project will be an ideal test platform for INTFES for optimal functional electrical stimulation in different patient groups. Topics that will be addressed in detail are (1) selective muscle control, (2) motoneuron stimulation vs. reflex stimulation, (3) avoidance of discomfort and pain during stimulation, and (4) conditions of muscle fatigue.

Conclusion and Outlook

We presented INTFES – a multi-pad electrode device for selective transcutaneous electrical muscle stimulation. Design characteristics of the device and advantages of the usage of multi-pad electrodes were discussed. It was shown that the use of array electrodes is highly promising. Nevertheless, further research efforts are needed – as for instance the research project HYPER – to exploit the full potential of this technology and make it ready for the market.

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