

Jan C. Loitz*, Aljoscha Reinert, Ann-Kristin Neumann, Fanny Quandt, Dietmar Schroeder and Wolfgang H. Krautschneider

A flexible standalone system with integrated sensor feedback for multi-pad electrode FES of the hand

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Abstract: Functional electrical stimulation aims to help patients suffering from stroke or spinal cord injury to supplement lost motor function. Effective functional electrical stimulation requires precise placement of the stimulation electrode. Finding the correct placement, however, can be difficult and time consuming. Another common problem with functional electrical stimulation is early occurrence of muscle fatigue upon repetitive stimulation, limiting treatment efficiency. Both, precise electrode placement as well as the reduction of muscle fatigue can be achieved using multi-pad electrodes. Here we present a new standalone device for multi-pad functional electrical stimulation. The device is easy to use and designed to help patients recovering from stroke to train and perform opening of the hand.

Keywords: electrode arrays; electrode placement; functional electrical stimulation; multi-pad electrodes; muscle fatigue; neuromuscular electrical stimulation; stroke.

1 Introduction

Neuromuscular electrical stimulation activates peripheral motor neurons with short electrical pulses delivered through the skin, thereby eliciting muscle contractions. Using these muscle contractions to supplement lost functions, e.g. after a stroke or spinal cord injury, is called functional electrical stimulation (FES) [1]. FES can be used

to achieve functional tasks such as walking, cycling or grasping [2]. The effect of FES does strongly depend on the precise placement of the stimulation electrode over the muscle motor point [3]. The motor point is the area where the desired stimulation effect is achieved with the least amount of current. Manual search for these motor points is possible but time consuming, especially for inexperienced users or impaired patients.

The usage of multi-pad electrodes is one way to ease the process of electrode placement and has been the topic of many studies in the last years [4–7]. One major concern performing neuromuscular electrical stimulation is the rapid occurrence of muscle fatigue, limiting treatment success [1]. Spatially distributed stimulation with multiple electrodes has shown some promising results to postpone muscle fatigue [8–10] and is an additional advantage of multi-pad electrodes. Most systems currently used for multi-pad FES require an external computer to control stimulation, complicating practical application of stimulation outside of the clinical setting.

In this paper, we present an easy to use, flexible standalone system for multi-pad electrode FES, which includes an automatic electrode search. It works without a computer and can be used with any electrical stimulation device.

2 System design

The presented system is designed for stimulation of the extensor digitorum muscle to achieve hand opening in stroke patients (see Figure 1). Flex sensors (Flex Sensor, Spectra Symbol, Salt Lake City, UT, USA) are attached to the fingers to measure finger movement upon stimulation. Multi-pad electrodes cover a large area over the extensor muscles of the forearm and an indifferent electrode is placed at the wrist. The major components of the devolved system are the multi-pad control hardware, custom-made multi-pad electrodes and a commercial stimulator (Motionstim8, Medel GmbH, Hamburg, Germany) (see Figure 2).

*Corresponding author: Jan C. Loitz, Institute of Nano- and Medical Electronics, Hamburg University of Technology, D-21073 Hamburg, Eissendorfer Str. 38, Germany, E-mail: jan.loitz@tuhh.de
Aljoscha Reinert, Ann-Kristin Neumann, Dietmar Schroeder, Wolfgang H. Krautschneider: Institute of Nano- and Medical Electronics, Hamburg University of Technology, D-21073 Hamburg, Germany

Fanny Quandt: BrainImaging and Neurostimulation (BINS) Laboratory, Department of Neurology, University Medical Center Hamburg-Eppendorf, D-20246 Hamburg, Germany

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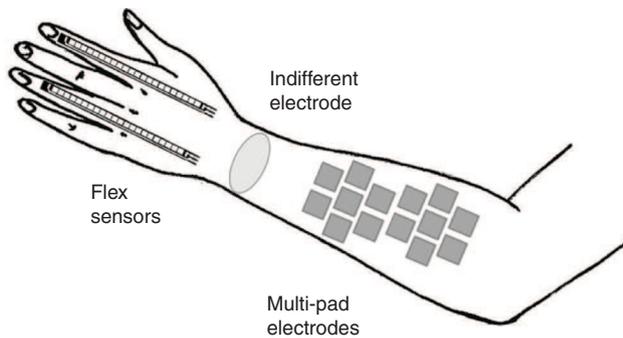


Figure 1: Schematic illustration of multi-pad electrode FES for hand opening with sensor feedback.

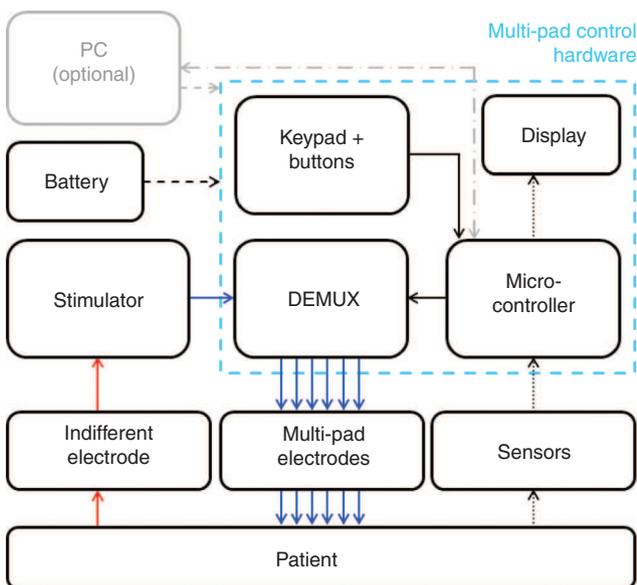


Figure 2: Block diagram of the multi-pad stimulation system and its components. Red and blue lines represent stimulation currents, solid lines control signals, dotted lines information, dashed dotted lines control signals as well as in information, and dashed lines power.

2.1 Multi-pad control hardware

Core of the multi-pad control hardware is an Arduino Due (AT91SAM3X8E microcontroller). The microcontroller communicates over SPI with a port expander (MAX7301) which switches reed relays. To switch the reed relays, Darlington transistor arrays are used. The port expander, Darlington transistors and reed relays build the demultiplexer (DEMUX). Each relay is connected in series with one electrode, which allows passing the stimulation current to a desired electrode by closing the normally open relay. The system supports up to 16 active electrodes.



Figure 3: Left: Multi-pad control hardware with keypad, display and front panel to connect electrodes and sensors. Right: Custom-made multi-pad electrode and sleeve.

To control the system, a keypad and two buttons are used. A display allows the user to navigate through different stimulation protocols. The multi-pad control hardware is displayed in Figure 3 [left]. Power supply is currently achieved over the micro USB-port of the Arduino Due. An external battery can be used to power the system. Flex sensors can be attached to the multi-pad control hardware to measure finger movement. Up to four sensors are supported at the moment.

Optionally, a computer can be connected via USB to control the system and to visualize sensor values more precisely, however, is not necessary for normal operation.

2.2 Multi-pad electrodes

Similar to [11] flexible printed circuit boards were designed and manufactured (LeitOn GmbH, Berlin, Germany). In contrast to some other multi-pad electrodes [4, 12] we chose square over rectangular or elliptical electrodes. The optimal electrode geometry depends on the orientation of motor axons or motor axon branches, which are unknown or hard to determine. Therefore square or round electrodes are favored [13]. Electrode size was $20 \times 20 \text{ mm}^2$ with a spacing of 5 mm. Each multi-pad consists of seven electrodes (see Figure 3 [right]). Two multi-pads with seven electrodes each can be used at the same time (see Figure 1), allowing an expert to place two additional electrodes manually.

The conductive electrode surface is made of electrodeless nickel immersion gold, which is a good conductor and suitable for transcutaneous applications without permanent skin contact [11]. A thin layer of immersion gold covers the nickel completely and prevents oxidation as well as direct skin contact. For skin contact a hydrogel layer is required. The hydrogel layer (e.g. AG700 Series

Hydrogel, Axelgaard, Fallbrook, CA, USA) allows a homogeneous current distribution and can provide adhesive contact to the skin. As an inexpensive alternative we used ultrasound gel (Seidel medipool GmbH, Buchendorf, Germany), which has similar conductive properties but no adhesive effect. The multi-pad electrodes were mounted in custom-made sleeves (see Figure 3 [right]) to secure arm attachment.

2.3 Stimulation protocols

One useful feature of the developed system is a search function, automatically determining the desired stimulation electrode. In this protocol single stimulation electrodes are activated successively and the finger movements are measured with the flex sensors. After the search protocol the two electrodes eliciting the greatest range of motion will be displayed for each flex sensor.

The actual stimulation protocol should be performed after appropriate electrode selection. There are three stimulation protocols realized so far: stimulation with one electrode, simultaneous stimulation with two electrodes as well as alternating stimulation with two electrodes. During alternating stimulation two relays will be switched with a certain frequency passing the stimulation current first through one and then through the other electrode. The switching frequency should match the stimulation frequency, reducing the stimulation frequency of each electrode in half.

3 System demonstration

Our stimulation setup can be seen in Figure 4. Flex sensors are attached to fingers with custom-made rings and are mounted to a wrist bandage, which also reduces wrist



Figure 4: Stimulation setup with flex sensors and multi-pad electrodes.

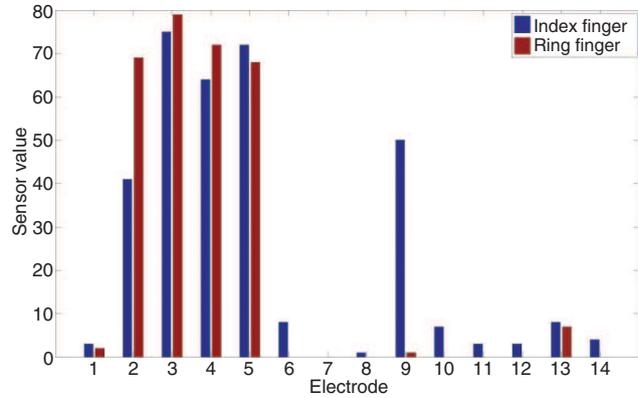


Figure 5: Maximal sensor values for each electrode during an electrode search protocol.

movement, with Velcro stripes. One commercial electrode (PALS, Axelgaard, Fallbrook, CA, USA) is placed at the wrist as the indifferent electrode and the multi-pad electrodes are attached to the arm using sleeves. All tests were performed with 30 Hz, 20–30 mA and 50–90 μ s.

Figure 5 shows the results of a search protocol with 14 electrodes and two sensors connected to the index and ring finger for one exemplary participant. The third and fourth electrode produced the greatest range of motion in the index finger, whereas the ring finger was moved the most by stimulation of electrode three and five. Overall, electrode three produced the greatest combined movement, followed by electrode five. Each stimulation lasted 3 s, followed by a 2 s break, resulting in a total duration of less than 90 s.

In Figure 6 single electrode stimulation of electrode three is compared to alternating stimulation of electrodes three and five for the same participant. In general it can be seen that alternating stimulation does work and can produce a steady hand opening, even though the sensor values during single electrode stimulation are more constant.

4 Discussion and conclusion

Here we present a newly developed multi-pad electrode FES system. The system is easy to use and does not require an external computer, making it more feasible for the practical application in patients. Importantly, attaching all electrodes and sensors and starting a search protocol takes <5 min. Even though here we demonstrate its use with the Motionstim8, it can also be combined with any other stimulator.

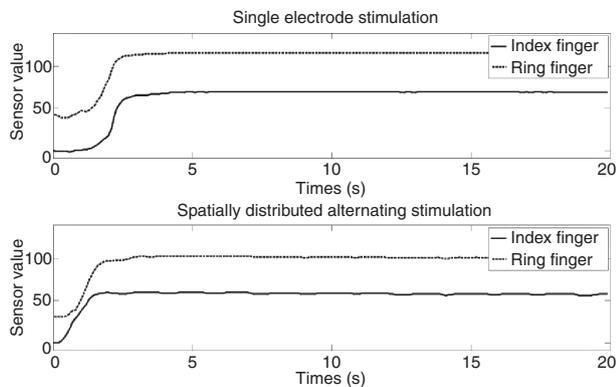


Figure 6: **Up:** Sensor data of index and ring finger during 20 s of single electrode stimulation. **Bottom:** Sensor data of index and ring finger during 20 s of alternating stimulation.

Spatially distributed alternating stimulation has been suggested as one way to reduce fatigue during FES [7–9]. The presented system allows alternating stimulation with two electrodes. We plan to assess the effectiveness of this technique in the future.

On the one hand multi-pads with smaller electrodes would provide an even more accurate search for the most effective stimulation electrode. Moreover, simultaneous activation of multiple electrodes to form virtual electrodes as well as alternating stimulation with more than two electrodes would become reasonable. On the other hand smaller electrodes would cover a smaller area, making placement of the multi-pad electrodes more difficult or would require a larger number of electrodes and relays, which would enlarge the hardware. Geometry, number of electrodes and material of the multi-pad electrodes are all items that may be optimized in the future, nevertheless the current version provides good results.

Having the hardware for demultiplexing of the stimulation current separated from the high voltage generation works as an additional safety layer. As long as the relays are open no stimulation currents can reach the patient.

The presented system offers a reliable and practical option to investigate the possibilities of multi-pad electrode FES.

Author's Statement

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the relevant national regulations, institutional policies and was performed in accordance with the tenets of the Helsinki Declaration, and has been approved by the authors' institutional review board or equivalent committee.

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