Stimulation Discomfort Comparison of Asynchronous and Synchronous Methods with Multi-Field Surface Electrodes

Eukene Imatz, Ulrich Hoffmann, Jan Veneman, Nebojša Malešević, and Thierry Keller

Abstract— **Functional Electrical Stimulation (FES) is a technique that artificially stimulates motor nerves in order to restore motor/sensory functions for assistive and therapeutic applications. Recently, multi-field surface electrodes for transcutaneous electrical stimulation have been suggested to overcome problems of single channel surface stimulation. This study compares sensation perceived by 15 healthy subjects on upper limb when two different stimulation methods are applied by means of multi-field electrodes. Asynchronous and synchronous stimulation methods are compared for four different cases: activation of two neighbor fields, three neighbor fields, two distant fields and three distant fields. Two descriptors rated from 1 to 5 are used to describe discomfort: superficial discomfort and deep discomfort. Results expressed no differences in superficial discomfort for any case, but showed significant differences in deep discomfort for distant field activations. In these cases, synchronous stimulation resulted in higher perceived deep discomfort than asynchronous stimulation and affected its efficacy.**

I. Introduction

Functional electrical stimulation (FES) artificially elicits muscle contractions and is used to restore lost or damaged sensory or motor functions. Successful FES motor restoring applications include respiratory support [1,2], bladder control [3], cardiac assistance [4], standing and gait assistance [5,6], or hand grasping support [7,8] among others. Application of FES for restoration of motor limb functions involves mainly spinal cord injury (SCI) and stroke subjects with upper or lower extremity motor control problems [9]. Although originally FES was thought to be used for motor function compensation, it has been proved to be successful also for therapy [10-14]. Regarding electrode types, lately, superficial hydrogel electrodes have become preferred over the implanted electrodes, especially in therapy due to the ease of donning and doffing them. These electrodes have some disadvantages such as reduced selectivity or potential discomfort resulting from the co-activation of sensory structures along with the targeted motor structures. High discomfort felt by patients can limit the effectiveness of FES, and thus, it is important to find stimulation methods that provide the intended performance while minimizing discomfort. Recent developments in novel multi-field electrodes have added a new dimension to surface electrical stimulation methods, by providing better selectivity [15,16] and algorithms for automatic determination of optimal stimulation parameters and electrode activation for a desired movement [16,17]. Asynchronous stimulation activates different electrode fields one right after the other, whereas synchronous stimulation activates different electrode fields all at the same time. As actual electrode configuration consists on a multi-field electrode placed over the targeted muscle group and a single anode placed on a location with no activation intention, the synchronous method normally results in more discomfort than asynchronous stimulation due to higher amplitudes going through the anode, as a result of the summation of the currents flowing through each single field. However, we wanted to see if when using synchronous stimulation with fields that were close to each other comfort improved, supposing that simultaneously activated neighbor fields would act like a bigger electrode [18] and lower current would need to go through the anode compared to asynchronous stimulation. This hypothesis needed to be tested, and therefore, in this study asynchronous and synchronous stimulation techniques are compared with respect to the achieved sensitivity.

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E.I. is with University of Basque Country and Tecnalia, Donostia-San Sebastián, Spain. (e-mail: eukene.imatz@tecnalia.com)

U.H. , J.V. and T.K. are with Tecnalia, Donostia-San Sebastián, Spain.

N.M. is with Tecnalia Serbia, Belgrade, Serbia.

I. Materials

A. IntFES Stimulator and multi-field electrodes

The FES device that we used in these experiments was the IntFES stimulator [19], which was designed for functional electrical therapy (FET). It is a single channel electronic stimulator that provides biphasic current-regulated stimulation. Multi-field electrodes, also called array electrodes, are electrodes that are divided into a certain number of fields or pads that can be activated independently and with different current amplitudes.

For the current experiments, we used one 16 field electrode array, which was specially designed for dorsal forearm stimulation [20] and it is shown in fig.1. Each field's size is 10x23mm, horizontal distance between fields is 2mm and vertical distance between fields is 3mm. The electrode uses a single layer of hydrogel with a high impedance in order to reduce current distribution inhomogeneities and improve comfort [21].

B. Wrist torque measuring system

A custom-built set-up shown in fig. 1 was designed and developed to measure wrist torque. The set-up was based on a JR3 force sensor with 6 degrees-of-freedom (DOF), which provided force and torque measurements in three axes: x, y, and z. Our solution consisted of an aluminum structure where the force sensor was integrated and the wrist was kept aligned with the Z-axis of the force sensor, which in fig. 1 would be coming out from the page. The force sensor was mounted between two aluminum plates. One of them was fixed and the other one had holes distributed along a circumference of 10 cm with the geometrical center aligned with the Z-axis. Holes had a separation of 10 degrees from -50 to 90 degrees. The aim of these holes was to hold a bar that fixed the position where the isometric torque measurement was made. Forces applied on this bar were directly transmitted to the aluminum plate and so, torque measured around Z axis will be directly the torque generated at the wrist. The parts of the system that supported the forearm and hand could be adapted to different hand and arm sizes. The force sensor produced an analog output that was recorded by a National Instrument NI-USB 6218 Data Acquisition Card (DAQ Card) and connected via USB to the PC.

C. *Graphical user interface (GUI)*

A custom-built GUI was designed to efficiently carry out the experiments. The interface was developed in Matlab® and its aim was to allow total and easy remote control and supervision of the experiments by the researcher. For this, it was essential that the GUI was able to a) communicate with the stimulator, b) receive, process and visualize data from the force sensor and c) store all the information including sensory ratings provided by subjects.

II. METHODS

The aim of the experiments was to investigate if significant differences in sensation were perceived between asynchronous and synchronous stimulation in a population of 15 healthy subjects. For this purpose, we decided to go for an isometric wrist torque measuring approach. Wrist extension was stimulated increasingly until a wrist extension of 45 degrees was achieved. From there on, due to the limiter in shape of a bar, a further increase of the stimulation amplitude resulted in an isometric contraction. Regarding sensitivity, the subjects were asked to rate their discomfort according to a rating scale, where minimum was 1 (no discomfort) and maximum was 5 (pain). Two descriptors were also defined to better describe their feeling, which were superficial or deep discomfort.

We compared asynchronous stimulation and synchronous stimulation. In these experiments, asynchronous stimulation activated selected fields one after the other with 2ms time separation, while synchronous stimulation activated all the selected fields at the same time. The pulse shape was biphasic current compensated, and stimulation parameters were frequency at 40Hz, pulse width at 250μs, 0.5s starting ramp, 6 seconds constant stimulation and 0.5s falling ramp for all the tests. While being stimulated, the subjects had to read, e.g. newspapers and magazines, to get distracted and to make sure that their hand was completely relaxed. Each of the methods was tested in each subject for four different cases, which were activation of two neighbor fields, two distant fields, three neighbor fields and three distant fields. Distant fields were defined as fields which had at least one other field between them.

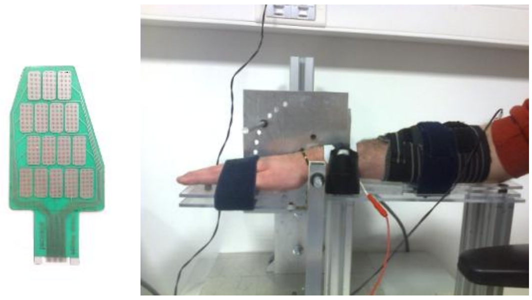

Figure 1. Multi-field electrode and experiment set-up.

The order of these tests was randomized for every subject so fatigue or getting accustomed to the sensation of FES throughout time would not affect the results.

The protocol involved two short adaptation sessions of 20 minutes two days before the main session. The aim of the adaptation sessions was to get subjects familiarized with sensations produced by FES before the main session was performed. The procedure followed in the main session was divided in four stages, which were donning, calibration, performance of the trials and doffing. The whole session lasted about 1h and 30 minutes. The experimental protocol was approved by the local ethics committee.

- Donning: Preparation stage consisted of putting the multi-field electrode over the extensor muscles of the forearm, attaching the anode on the wrist, correctly seating the subject in the chair and aligning the wrist with the force sensor using Velcro straps.
- Calibration: The aim of the calibration stage was to define the reference amplitude and optimum fields for each of the four cases. Initially, the amplitude was increased gradually until the target of 45 degree wrist extension was achieved with a single field. After the target was reached, each of the 16 fields was activated with this amplitude. Then four possible configurations for the four cases were defined, selecting those fields which reached the target producing higher torque. Sometimes the initial amplitude had to be increased to reach the target with each of the selected fields for the four cases. Finally, we defined the reference amplitude as the amplitude with which the subject reached the target when activating independently each of the selected fields.
- Trials: In this stage, comparison between methods was performed and the following sequence was followed for each of the four cases. First of all, the selected fields were separately activated with the reference amplitude defined in the calibration stage. The reference torque was then defined as the maximum torque reached by any of the separately activated fields. Once the reference torque was obtained, previously selected fields were activated with one of the methods in random order. First low amplitude was used, 6mA lower than reference amplitude, and it was increased 1mA at a time until 45 degree extension was reached and reference torque was exceeded. At this point, subjects were asked to rate their discomfort. If any subject felt high discomfort or pain and did not want to go higher on amplitude before target was reached we considered it an

unsuccessful test, but subject was equally asked to rate his feeling. These last steps were repeated with each of the methods and the whole procedure presented in this stage was repeated four times, one for each case.

- Doffing: Finally, electrodes were detached and Velcro straps were loosened.

III. Results

A. Activation

We considered that a test was successful if the 45 degree extension was achieved and the reference torque was exceeded. If pain or big discomfort felt by the subject prevented us from achieving this target we considered it an unsuccessful trial. In fig. 2 we can see that asynchronous method was successful in 14 people independent of the case, while synchronous method showed differences depending on the case, especially in distant field cases, where the amount of successes was smaller. 5 subjects did not achieve the target when two distant fields were synchronously activated and 4 subjects when three distant fields were synchronously activated. It is important to point out that subjects that failed to success with synchronous stimulation described high discomfort or pain on the wrist, where the anode was located. It also has to be mentioned that one of the 15 subjects turned out to be very sensitive to electrical stimulation and only reached the target in one case, which was synchronous activation of three neighbor fields. In Table I achieved final amplitude ranges of the 15 subjects for each case are shown.

B. Discomfort

Discomfort was described by two descriptors, which were superficial and deep discomfort. Each of them was rated from 1 to 5 either when the subject reached the target or when the subject wanted to stop increasing amplitude due to a very uncomfortable feeling. Fig. 3 shows medians and interquartiles for each case and each descriptor. Differences in the median values are seen for asynchronous and synchronous methods, especially in superficial discomfort ratings for near field cases and deep discomfort ratings for distant field cases. However, the variability in the discomfort ratings was considerably high due to the large inter-subject variability in sensitivity to electrical stimulation.

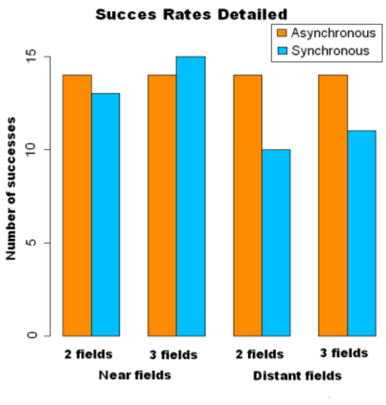

Figure 2. Number of successes for each case.

TABLE I. Amplitude ranges

		Case	
		Asynchronous	***Synchronous***
Near fields	***2 fields***	16-25mA	9-15mA*
	3 fields	14-22mA	6-10mA*
Distant fields	***2 fields***	12-25mA	9-17mA*
	3 fields	13-22mA	7-13mA*

* Note that this was the amplitude of each field, so total amplitude at the anode was this value multiplied by the number of active fields.

To avoid the inter-subject variability problem and detect significant intra-subject differences on discomfort between both methods, paired Wilcoxon statistical tests were done. First, each case was separately analyzed but no significant differences were found due to the small size of the samples. Thus, these four cases were grouped into two cases in two different ways: 2 field and 3 field cases; and near field and distant field cases. Deep and superficial discomfort rating differences were again analyzed by Wilcoxon paired tests. 2 field and 3 field groups showed no significant difference between methods for any descriptor. For near field and distant field groups, results shown in Table II present no significant differences in superficial discomfort between asynchronous and synchronous methods. Regarding deep discomfort, results showed also no significant differences for near field cases. However, test results proved that there is a significant difference between both methods for deep discomfort ratings in distant field stimulation.

IV. Discussion

Results showed that synchronous stimulation produces more discomfort than asynchronous stimulation when distant fields are activated with this array electrode configuration. Indeed, subjects pointed out that the discomfort was located around the wrist. This supports our hypothesis, which suggested that this effect is caused by high amplitude currents flowing through the anode in synchronous stimulation, which is the sum of amplitudes on each field. However, this effect was not a problem in near field cases, since lower amplitudes were needed to achieve the target. This fact also supports the suggested hypothesis, which states that synchronously activated neighbor fields might act like a bigger electrode.

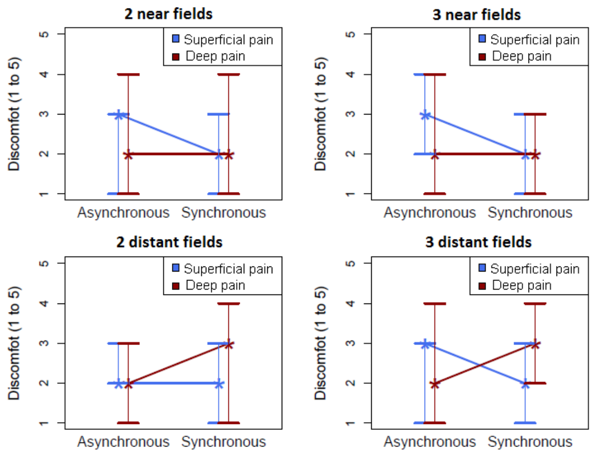

Figure 3. Discomfort rate medians and interquartiles.

TABLE II. WILCOXON PAIRED RESULTS

		Case	
		Near fields	***Distant fields***
Discomfort type	***Superficial***	p = 0.1677	p = 0.1155
	Deep	p = 0.4644	p = 0.01562[a]

a. Discomfort differences between methods are significant in this case.

Differences in discomfort for distant fields affected stimulation effectiveness, as 5 (with two activated fields) and 4 people (with three activated fields) failed to success reaching the target with synchronous stimulation due to pain or big discomfort. Regarding near field activation with synchronous stimulation, we got better results than with distant field activation, but we did not see any significant improvement with respect to asynchronous stimulation. In fact, asynchronous stimulation showed stable discomfort rates and successful attempts for all the cases.

Considering that a stimulation method should give the possibility of successfully using the widest variety of field activation patterns as possible in order to obtain a better selectivity, asynchronous stimulation has shown to be the best option between both methods using multi-field electrodes. However, in further studies, new stimulation techniques, new electrode configurations and combinations of these should be tested so that optimum stimulation methods for multi-field electrodes can be defined in terms of sensitivity, performance and selectivity.

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