Transcutaneous FES-induced pain maps on post-stroke upper limb

Preliminary study

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Abstract—**Functional Electrical Stimulation (FES) is a technique to artificially stimulate motor nerves in order to restore motor/sensory functions for assistive and therapeutic applications. This preliminary study attempts to detect differences in the perception of transcutaneous FES in upper limbs. Three chronic stroke survivors participated in the study. Multi-field electrodes were used to selectively activate the targeted areas over the wrist-finger flexors, wrist-finger extensors, biceps, and triceps muscles. Results showed no significant correlation between the applied current and pain ratings. Differences in the rating of pain in different fields over the four targeted areas were observed. The initial results suggest that here is a common pattern to most subjects for each area of the upper limb.**

Index Terms— **FES, pain, upper limb, neuroprosthesis, transcutaneous electrodes**

I. INTRODUCTION

Transcutaneous FES artificially elicits both motor and sensory nerves and produces muscle contractions to achieve functional movements. The main applications of FES are within the rehabilitation field, in which this technique is used to aid recovery or to restore lost or damaged sensory/motor functions [1-5]. Transcutaneous FES applies current pulses through the electrodes placed on the skin surface and therefore, it excites both afferent and efferent neuronal structures. Sensory receptors located on the skin comprise a) cutaneous and subcutaneous mechanoreceptors, which are able to perceive pressure, texture, stretch or vibration; b) thermal receptors, responsible for perceiving temperature; c) nociceptors, which perceive pain caused by strong tactile stimuli, extreme temperatures or a variety of destructive stimuli; and d) muscle and skeletal mechanoreceptors, which provide proprioceptive information of the body [6]. Although results from some sensitivity studies give us a notion of the tactile spatial acuity variation over different areas of the body [7-9], there is no detailed knowledge about spatial distribution of sensory receptors on the arm. These neural structures located in the different layers of the tissues are excited when transcutaneous FES is applied [10]. With increasing intensity, first larger touch sensory nerves (Aα-fibers) and last pain sensory fibers (Aδ-fibers) are excited, which can result in discomfort or pain in some subjects. Transcutaneous electrode technology has improved significantly through the years and recent developments in multi-field electrodes are slowly overcoming selectivity issues related to transcutaneous stimulation [11,12]. However, the effectiveness of transcutaneous FES is sometimes limited due to the discomfort felt by the subject, and thus, it is important to find techniques that avoid causing pain or discomfort during application of transcutaneous electrical stimulation [13]. Hence, this preliminary study attempts to get sensitivity differences upon application of transcutaneous FES in the upper limb. The aim was to detect common patterns or trends in terms of spatial distribution of pain sensation and identify commonly painful areas. An electrotactile two-point discrimination sensitivity study was carried out on different parts of the body [7], however, this study focused on sensory aspects, ignoring functional aspects of electrical stimulation. In the present study, a protocol was designed in order to get pain ratings related to motor threshold values so functional properties were considered. This preliminary study intends to be the first step in the process of obtaining pain maps in the upper limb that will serve as a basis for the design of more effective and comfortable transcutaneous neuroprostheses.

II. MATERIAL

Two different transcutaneous electrical stimulation devices were used in this pilot study. Adaptation sessions for the subjects to become familiar with FES were carried out with commercial Cefar Rehab X2 [14] stimulators, whereas the main session was carried out with the second version of the IntFES system [15].

The IntFES system was used in the main session because it has been designed to work with multi-field electrodes. IntFES is a single channel electrical stimulation system that provides biphasic current-regulated stimulation pulses. It is designed to activate asynchronously or synchronously up to 4 multi-field electrodes with up to 16 fields each. A regular matrix shown in Fig. 1 was designed for this pilot study in order to: a) be
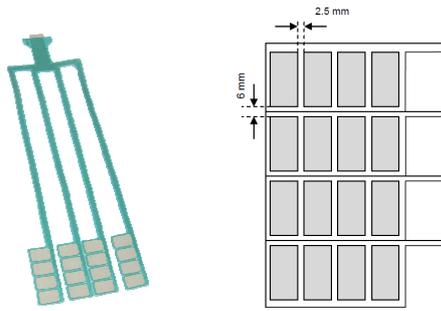
Fig. 1. Multi-field electrodes used for pain map experiments.

flexible to adapt to different arm sizes and shapes and b) cover the maximum area to obtain complete pain maps. A common anode of size 50x50mm was used, and the size of each field was 30x15mm.

III. METHODS

The objective of this pilot study was to check if there was a common pattern within subjects regarding sensation in different areas of the upper limb. For this purpose, experiments were carried out in three volunteer chronic stroke subjects. The protocol consisted of an adaptation phase carried out at home to become familiar with FES and a main session of 90 minutes held in LAMBECOM lab. The protocol was approved by the ethical committee of Universidad Rey Juan Carlos and all the participants signed an informed consent.

A. Subjects

Three volunteer chronic stroke subjects were included in this pilot study. None of them suffered from aphasia and they had the cognitive ability to understand, follow and participate in the study without any difficulties. All of them were suffering from hypoesthesia on the affected arm and they were evaluated with the Fugl-Meyer assessment tool [16] before adaptation sessions took place. Additional details are listed in Table I.

B. Adaptation sessions

The aim of these sessions was to make the subjects familiar to the feeling of transcutaneous electrical stimulation before carrying out the main session. Cefar Rehab X2 standard commercial neuromuscular stimulators were delivered to the subjects and they were told to run the program 19 (20 minutes) twice a day in the four areas (wrist-finger flexors, wrist-finger extensors, biceps, and triceps) during the week before the main session.

C. Main session

Parameters during the whole session were set to a stimulation frequency of 25Hz, a pulse width of 200 µs and initial and final amplitude ramps of 0.5s. The multi-field electrodes were placed over the four different areas of the arm: wrist-finger extensors, wrist-finger flexors, biceps, and triceps. Lateral and medial epicondyles were taken as a reference for electrode placement as shown in Fig. 2 the following procedure was carried out for each of the 16 fields of each area:

TABLE I. SUBJECTS

Subject	Age	Hemiplegia	Years from stroke	Sensation score [a]
1	67	Right	8	8
2	54	Right	4	6
3	40	Left	13	10

a. Score corresponding to the sensation section of Fugl-Meyer, where maximum score is 12.

- Randomly select a field and set it with 0 mA
- Increase amplitude in steps of 1mA until visually perceiving a weak contraction (motor threshold).
- If no contraction was obtained at 25mA or the subject could not tolerate an amplitude of two times motor threshold, next steps were skipped.
- Double motor threshold amplitude and stimulate during 5 seconds.
- Ask subject to rate pain on a visual analog scale (VAS)
- Note down the motor threshold amplitude and the rated pain for the selected field.

IV. RESULTS

The ranges of pain ratings and motor threshold values collected for each of the four areas and each of the three subjects are summarized in Table II.

A. Normalized Motor Threshold Maps

Data from each patient and each of the four stimulation areas were normalized. In order to be able to compare and to visualize the motor threshold values of both left and right side affected subjects, data from left arm affected subjects was mirrored, so all the graphs show the same representation. The individual motor threshold values of the three subjects are shown in Fig. 3, where each graph represents the area covered by the multi-field electrode placed as shown in Fig. 2. The color of each field represents the motor threshold that corresponds to the activation of the area that is underneath. Darker colors (dark blue) represent fields with higher motor threshold, accordingly, lighter colors (light blue) represent areas with lower motor threshold. Grey fields represent areas where no contraction was achieved when at least 25mA were applied.
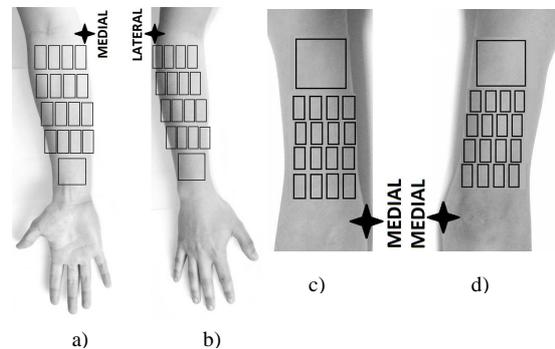
Fig. 2. Electrode position example with medial and lateral epicondyles as references: a) flexors b) extensors c) biceps and d) triceps.

TABLE II.   Pain Rating and Motor Threshold ranges

Area	Subject	PR range (0-10 scale)	MT range (mA)
Flexors	1	1-5	6-13
	2	4-5	8-16
	3	0-1	8-13
Extensors	1	1-2	7-16
	2	1-3	8-16
	3	0	10-15
Biceps	1	1-4[a]	3-17
	2	2-6	5-18
	3	0-3	6-18
Triceps	1	1-3[a]	8-20
	2	2-4	8-18
	3	0-3[a]	13-19[a]

a. Ranges where there is at least one missing value.

Although inter-subject variance was high, we can see from Fig. 3 that there were some common fields that got higher motor threshold values than the rest. Over the wrist-finger extensor area, the most distal fields got the higher motor threshold values and similarly, high values were recorded on the proximal fields on biceps and triceps for the three subjects.

B. Normalized Pain Rating Maps

Analogous to the motor threshold maps, pain maps are shown in Fig. 4, where each graph represents the area covered by the multi-field electrodes placed as shown in Fig. 2.

The color of each field represents the pain rating that corresponds to the activation of the area that is underneath. Darker colors (red) represent fields that got higher pain ratings, accordingly, lighter colors (light yellow) represent less painful fields. Grey fields represent missing pain ratings. Similar to motor threshold case, in Fig. 4 we can see that there were some common fields that seemed to be more painful than the rest. High pain ratings were recorded on the proximal fields on biceps and triceps for all subjects. However, in contrast to motor threshold maps, the higher pain ratings over the wrist-finger extensor area were recorded on the proximal lateral fields, except on subject 3, who was not able to perceive any difference among fields in this area.

C. Pain Rating vs. Motor Threshold Correlation

In order to find if perceived sensation variation among fields was only an effect of current amplitude (motor threshold multiplied by two) variation, Kendall´s tau-b [17] was calculated for each area and each subject. Individual tests only proved a significant correlation in biceps for subjects 1 and 2 with $p < 0.01$. No significance was found between pain ratings and applied currents for wrist-finger extensors, wrist-finger flexors or triceps areas, which means that high pain ratings did not always correspond to high motor threshold values and vice versa.
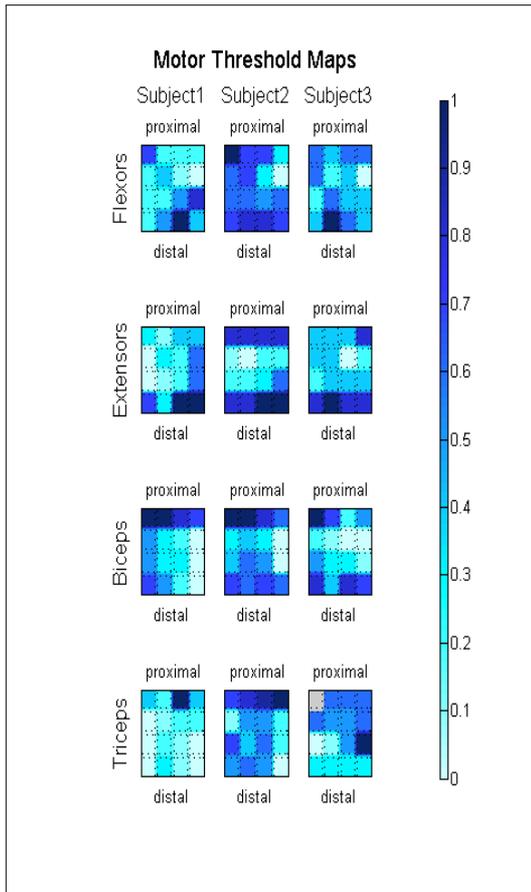
Fig. 3. Motor threshold maps
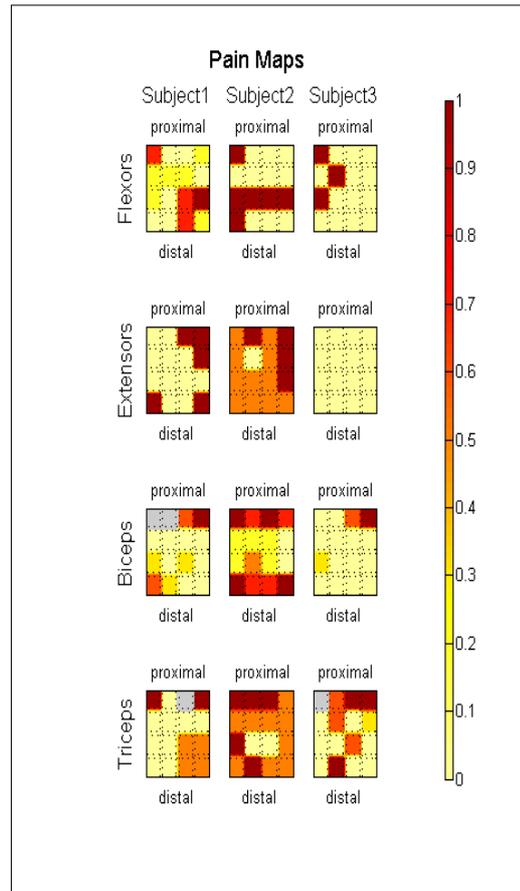
Fig. 4. Pain maps

V. Discussion

Results of this preliminary study showed that there were variations in perceived sensation among different fields within each area of the upper limb for all subjects. This fact can be a result of two factors, which are a) differences in density and spatial distribution of receptors over the skin on the upper limb and b) differences on applied current amplitudes on different fields. Results showed no significant correlation between the applied current and pain ratings except in the biceps for two of the subjects. This fact supports the hypothesis that some areas are more painful than others independently of the applied current and can be due to spatial distribution of sensory receptors on the skin. However, this lack of correlation can also be a result of current amplitude ranges, because subjects could not easily distinguish perceived pain if applied amplitude ranges were not wide enough. As we can see in Table II, subjects were able to perceive more differences in terms of pain among fields in biceps area, which is also the area that got the widest motor threshold ranges in all subjects. In any case, most subjects could feel some differences in pain within all areas. Furthermore, some specific fields in the wrist-finger extensors, biceps and triceps got the highest pain ratings from all subjects, especially proximal fields on biceps and triceps, which suggests that application of FES over these points on the upper limb, is more susceptible to induce pain or discomfort. This could be a result of a) the spatial distribution of sensory receptors, where FES recruits a bigger amount of sensory receptors in those areas where there is a high density of receptors, or b) the high amplitudes needed to evoke a contraction when FES is applied in those areas, which results in the recruitment of a wider variety of receptors such as nociceptors. In any case, areas that result to be most painful within the different parts of the upper limb should be considered in FES applications and avoided when possible to allow comfortable neuroprostheses. To conclude, in order to verify if differences on pain perception of different fields are significant and find if there exists a common trend to most subjects, a further study with a larger group of subjects should be carried out. Results of pain maps based on empirical data indicating most painful and least painful areas upon application of transcutaneous FES could be a good basis for the design of neuroprostheses when combined with functionality studies.

Acknowledgment

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