Selective Activation of Pig Forearm Muscles using Thin-Film Intrafascicular Electrodes Implanted in the Median Nerve

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Abstract

The quality of functional electrical stimulation (FES) systems is limited by the recording quality and the stimulation selectivity of the neural interface it uses. Thus advances in the quality of the neural interface can directly improve what can be offered by the FES system. The objective of the present study was to investigate the stimulation selectivity of the thin-film longitudinal intrafascicular electrode (tfLIFE) in a large-nerve animal model. Two double sided 8-channel tfLIFE’s (top and bottom side each 4 contacts) were placed in the median nerve in pigs and stimulation was applied for 28 contact combinations (range: 20 µA - 540 µA). Surface EMG responses were recorded from seven forelimb muscles and V_{pp} values were evaluated at a 2-12 ms post stimulation interval. A selectivity index (SI) was calculated to reflect the degree of evoked muscle activity of each individual muscle with respect to the whole set of muscles. Preliminary results show that selective activation of flexor and extensor muscles can be obtained. For example, for different contact combinations, the flexor carpi radialis muscle showed a SI = 68% (I=200 µA) and the biceps muscle showed a SI = 79% (I=240 µA). As such, the tfLIFE electrode provides selective activation of muscles, which may be of paramount importance for advanced degree of freedom prosthetic limb control.

1 Introduction

The success of functional electrical stimulation systems are today mainly limited by the quality of the information recorded by the electrodes and by lack of selectivity to activate independent muscles. Nerve cuff electrodes have long shown the ability to provide a chronic reliable interface to record from or activate peripheral nerves, and are to date probably the most successful and widely used chronic peripheral interface in animal preparations and in humans. In spite of the major success of the cuff electrodes, they can only provide a relatively small number of channels of information. Previous work have investigated the stimulation selectivity of multi contact cuff electrodes in different animal models as well as in humans [1-3], but the degree of selectivity was limited. Therefore, a different type of neural interface that does provide a larger selectivity may be needed to improve the functionality of existing prosthetic devices.

Intrafascicular electrodes (LIFE’s) were developed to provide a more selective interface by placing the recording/stimulating sites within the nerve fascicle [4-6]. This is achieved by using a tungsten needle to penetrate the nerve sheath and position the electrode inside the nerve. In this way, multiple recording or stimulation sites can be introduced in very close proximity to individual nerve fibers. The LIFE’s have previously shown promising results as a neural interface with high selectivity [4-6]. Recently, we have developed a micro-fabricated, multi-site, thin-film on polymer substrate version (tfLIFE) [7]. Each structure currently carries of an array of 8 contact sites, divided into a row of 4 evenly spaced contacts on both the top and bottom side.

The aim of the present study was to investigate the degree of stimulation selectivity that can be obtained with a tfLIFE electrode in an animal model with nerve size similar to humans. Acute animal experiments were performed, and preliminary results from one animal experiment are presented.

2 Material and Methods

2.1 Animal preparation

All experimental procedures were approved by the Animal Experiments Inspectorate under the Danish Ministry of Justice. Experiments were carried out on six female Landrace-Yorkshire pigs placed under general anaesthesia (Isoflurane). With the animals in supine position, access to the median nerve in the left leg was achieved through the axilla. Two 8-channel thin-film longitudinal intrafascicular electrodes (tfLIFE) were implanted in the median nerve just proximal to the elbow joint. The electrodes were implanted in an angle of approximately 45° to cover as much of the cross sectional area of the median nerve as possible. Furthermore, one electrode was positioned medial-to-lateral (M-to-L) in the nerve and the other electrode was placed in the lateral-to-medial (L-to-M) direction. The eight electrode sites are referred
to as: ['1t', '1b', '2t', '2b', '3t', '3b', '4t', '4b']

where e.g. electrode site '1t' is placed most distal and on the top side and '4b' is placed most proximal on the bottom side of the electrode, see Fig. 1. The electrodes were manufactured by the Fraunhofer Institut Biomedizinische Technik (IBMT), Dept. Medical Technology and Neuroprosthetics, Germany. Bipolar patch electrodes were sutured on the surface of seven muscles, as close to the innervation points as possible. Five flexor muscles were chosen (M1: flexor digiti II, M2: flexor carpi radialis, M3: flexor digit superficialis, M4: flexor carpi ulnaris, M5: flexor digit superficialis (deep belly)) and two extensor muscles (M6: extensor carpi radialis, M7: brachialis). The patch electrodes were fabricated using stainless steel wires (AS632, Cooner Wire Co, USA) of which the ends were de-insulated and woven through a piece of Dacron reinforced silicone sheeting to create active contacts on one side while medical grade silicone (MED 1037, NuSil, Sweden) was applied on the other side to fix the wires in position and obtain and electrically isolating non-active side.

2.2 Data acquisition and processing

A programmable, multichannel electrical stimulator (STG2008, Multi Channel Systems) was used to apply controlled current pulses to the different electrode contacts. Stimulation was performed between contacts of each of the tfLIFE electrodes using monophasic, rectangular pulses with amplitudes ranging from 20 - 540 µA (duration 100 µs, frequency 2 Hz, 5 repetitions per level, 20 stimulation levels). The stimulation sequence was controlled via a USB connection between the stimulator and a laptop computer. The EMG activities from seven lower forelimb muscles were recorded in response to intra neural stimulation. The EMG activity was streamed to hard disk (HD24, Alesis) for offline analysis. The offline analysis consisted of band-pass filtering (20 Hz to 2 kHz), quantifying the peak-to-peak amplitude ($V_{pp}$) within a defined response time window (2 - 12 ms after onset of stimulation) and normalizing the value to the maximum $V_{pp}$ of each muscle in the experiment. A response threshold of 5% of maximum activation was then defined for each channel. Finally, the degree of muscle selectivity to the intra-neural stimulation was assessed through a selectivity index (SI), defined as the ratio between the normalized $V_{pp}$ of that muscle and the sum of normalized $V_{pp}$ of all muscles.

3 Results

Analysis of the complete data set of 6 pigs is still ongoing and therefore we present only preliminary results from one experiment in this paper. Contact-to-contact stimulation resulted in 28 different contact combinations. Stimulation always evoked a direct muscle response but, depending on the contact pair and the level of stimulation current, this was in some cases also followed by both short-latency and/or long-latency reflex responses (see Fig. 2).

Fig. 1. Picture of an 8-channel tfLIFE electrode. The orientation of the two inserted electrodes and the electrode sites inside the nerve (labelled "1t" to "4b") is shown in the inset.

Fig. 2. EMG response recorded from flexor muscle M1 while stimulating a selected pair ('1t-4t') of active sites in the M-to-L tfLIFE. The two vertical dashed lines mark the 2 - 12 ms time window used to include only the direct muscle response for analysis.

Fig. 3. Comparison of normalized $V_{pp}$ EMG responses from all seven muscles while stimulating a selected active site pair in the M-to-L electrode at the 20 different stimulation levels (top: contact sites '1t-2t', bottom: contact sites '3t-2b').
Figure 3 shows two representative plots of normalized EMG responses from all seven muscles while stimulating between specific contact sites in the M-to-L electrode. In the top figure the ‘1t-2t’ electrode site combination was used for stimulation, whereas in the bottom figure the ‘3t-2b’ combination was used. By comparing the two figures it is clear that the ‘1t-2t’ combination mainly activates the extensor muscles (M6-M7), whereas the ‘3t-2b’ combination mainly activates the flexor muscles (M1-M5).

![Fig. 3: Representative plots of normalized EMG responses from all seven muscles while stimulating between specific contact sites in the M-to-L electrode.](image)

The selectivities calculated to evaluate the degree of independent muscle recruitment for the seven muscles, are shown Fig. 4. EMG responses obtained for the lower range of stimulation currents remained below threshold and were therefore not considered in the SI calculation, resulting in the blank spaces in the plots. The highest selectivity index for the ‘1t-2b’ electrode site combination was found for the M7 extensor muscle at 79 % (stimulation current = 200 µA). In comparison, stimulation of the ‘3t-2b’ active sites, selectively activated the flexor M2 muscle at 68 % (stimulation current = 240 µA). In both two cases, the selectivity index of the other six muscles was less than 10 %.

![Fig. 4: Comparison of the selectivity index (SI) from all seven muscles while stimulating a selected active site pair in the M-to-L electrode at the 20 stimulation levels (top: contact sites ‘1t-2t’, bottom: contact sites ‘3t-2b’).](image)

**4 Discussion and Conclusions**

Muscles of the lower forelimb in the pig animal model were used to monitor and investigate the stimulation selectivity of the thin-film longitudinal infracuticular electrode (tFLIFE). Based on the calculated selectivity index, we observed that close to independent activation of muscle flexors and extensors was possible. The degree of selective muscle activation was dependent on the electrode contact combinations and the amplitude of the applied stimulation used. However, the largest selectivity for a specific muscle was in general obtained for lower degrees of activation, suggesting a close proximity of more than one fascicle to the active electrode site and early spillover. This demonstrates the challenges for obtaining selective activation in large nerve animal model compared to previous selectivity studies on the sciatic nerve containing only a limited number of fascicles [1]. Furthermore, inclusion of observed reflex muscle responses in the analysis could provide further information on the type of fascicles, i.e. if sensory and/or motor units, are activated. Use of the tFLIFE electrode may thus offer possibilities for selective muscle activation that are of paramount importance for advanced degree of freedom prosthetic limb control.

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**6 References**