Journal of Neuroscience Methods 172 (2008) 294–302

Contents lists available at ScienceDirect

Journal of Neuroscience Methods

journal homepage: www.elsevier.com/locate/jneumeth

On the use of wavelet denoising and spike sorting techniques to process electroneurographic signals recorded using intraneural electrodes

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ARTICLE INFO

Article history:
Received 27 November 2007
Received in revised form 3 April 2008
Accepted 25 April 2008

Keywords:
ENG signals
Spike sorting
Neuroprostheses
Intraneural interfaces
Bionics
Bio-robotics
Neuro-robotics
Cybernetic prostheses

ABSTRACT

Among the possible interfaces with the peripheral nervous system (PNS), intraneural electrodes represent an interesting solution for their potential advantages such as the possibility of extracting spikes from electroneurographic (ENG) signals. Their use could increase the precision and the amount of information which can be detected with respect to other processing methods.

In this study, in order to verify this assumption, thin-film longitudinal intrafascicular electrodes (tfLIFE) were implanted in the sciatic nerve of rabbits. Various sensory stimuli were applied to the hind limb of the animal and the elicited ENG signals were recorded using the tfLIFEs. These signals were processed to determine whether the different types of information can be decoded. Signals were wavelet denoised and spike sorted. Support vector machines were trained to use the spike waveforms found to infer the stimulus applied to the rabbit. This approach was also compared with previously used ENG-processing methods.

The results indicate that the combination of wavelet denoising and spike sorting techniques can increase the amount of information extractable from ENG signals recorded with intraneural electrodes. This strategy could allow the development of more effective closed-loop neuroprostheses and hybrid bionic systems connecting the human nervous system with artificial devices.

1. Introduction

Interfaces with the peripheral nervous system (PNS) can be used as a means to create a bi-directional link between the user's nervous system and an artificial device. The neural prosthetic interface can be used to induce activity in nerve fibers through electrical stimulation to place information into the nervous system. Conversely, information from the nervous system could be retrieved by recording the electrical activity of the nerve. Given a chronically stable device acting on an appropriate set of nerve fibers, such an interface could be used as part of a functional electrical stimulation (FES) system to restore function to paralyzed limbs (Popović et al., 1993) or in a brain-controlled robotic limb application (Micera et al., 2006).

In all these applications, the processing of raw electroneurographic (ENG) recordings from the neural interface can be used to reduce noise and to estimate the neural information source. Currently, there are various electrodes under investigation as neural interfaces (see Navarro et al., 2005, for a review on the available electrodes). Their characteristics determine the choice of the signal processing method. Electrodes with limited selectivity (e.g., cuffs) can, generally, only record the compound activity formed by the superposition of action potentials belonging to many axons. Therefore, in most cases, the neural activity recorded in this way has been used for onset detection, for example for the control of a 1-DoF hand prosthesis (Stein et al., 1980) or of FES-systems in hemiplegics Hoffer et al. (2005). Even if these limits can be partly overcome by using multi-site cuff electrodes (Yoo and Durand, 2005) and advanced processing techniques (Micera et al., 2001; Cavallaro et al., 2003; Lin et al., 2007; Tesfayesus and Durand, 2007), more selective PNS interfaces may be necessary to access more specific information. In fact, higher selectivity interfaces make possible the identification of single spikes from single axons (or a small group of axons) and to access the nat-

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doi:10.1016/j.jneumeth.2008.04.025

ural frequency coded information (Micera et al., 2006) in ENG signals.

Among the possible choices, intraneural electrodes represent an interesting solution because of their trade-off between invasiveness and selectivity (Yoshida and Stein, 1999; Warwick et al., 2003; McDonnall et al., 2004). In particular, longitudinal intrafascicular electrodes (LIFEs), which are wire-based electrodes inserted longitudinally into the nerve (Li et al., 2005; Lawrence et al., 2004), have been used in the past (Goodall and Horch, 1992; McNaughton and Horch, 1994; Mirfakhraei and Horch, 1997) to identify single units in multi-unit peripheral nerve recordings using different features and classification schemes. For example, artificial neural networks allowed differentiation of four to five units with a 70–90% reliability with single channel or differential recordings and a 90–98% reliability with dual channel recordings (McNaughton and Horch, 1994).

These very promising results could be improved by using different processing algorithms. For example, wavelet denoising techniques have been shown in the past to be a valuable tool for the analysis of signals recorded from the central nervous system (CNS) (Oweiss and Anderson, 2001; Nenadic and Burdick, 2005) and from the PNS during microneurography (Diedrich et al., 2003).

At the same time, the selectivity of intraneural electrodes (e.g., extraction of single units) enables the development of approaches based on spike sorting techniques borrowed from cortical array signal processing (Wheeler and Heetderks, 1982; Bankman et al., 1993; Lewicki, 1998; Welsh and Schwarz, 1999; Schwartz, 2004; Zhang et al., 2004; Bar-Hillel et al., 2004; Nenadic and Burdick, 2005).

The combined use of wavelet denoising and spike sorting algorithms could increase the amount of information that is decoded from intraneural recordings in the PNS. This could allow the development of more effective neuroprosthetic systems.

The aim of the present study was to assess the performance of these methods while decoding neurally derived information recorded by using intraneural electrodes. The approach proposed in this manuscript was further compared with other previously used algorithms.

2. Methods

2.1. Experimental setup

2.1.1. Thin-film LIFEs

A new version of the LIFEs, named the thin-film LIFEs (tfLIFE) was used in the experiments (Yoshida et al., 2006; Hoffmann and Koch, 2005). These electrodes were developed on a micropatterned polyimide substrate which was chosen because of its biocompatibility, flexibility and structural properties (Stieglitz et al., 2005). After microfabrication, this substrate filament (shown in Fig. 1) is folded in half so that each side has four active recording sites. Therefore, tfLIFEs allow multi-unit peripheral nerve recordings at eight recording sites per structure. A tungsten needle linked to the polyimide structure is used for implanting the electrode and is removed immediately after insertion.

2.1.2. Animal preparation

The experimental procedures were approved by the Danish Committee for the Ethical Use of Animals in Research. A set of protocols, including the one described in this paper, was carried out on a total of six adult (8–9 months old) female New Zealand White rabbits of approximately 4–4.5 kg. Anaesthesia was induced in the rabbits using an intramuscular injection of a Hypnorm/Dormacrom cocktail (0.15 mg/kg Midazolam (Dormicum, Alpharma A/S, Norway), 0.03 mg/kg Fetanyl and 1 mg/kg Fluranison combined in Hypnorm, Janssen Pharmaceutica, Belgium). tfLIFEs were implanted through a lateral access to the sciatic nerve between the biceps femoris and abductor cruris cranialis muscles. A second posterior access was created to expose the popliteal fat pad, which was removed to allow visualization of the branches of the sciatic nerve. The medial gastrocnemius nerve and lateral gastrocnemius/soleus nerves were identified by visual inspection, and by tracing the nerve to the muscle.

2.1.3. Sensory stimuli

The protocol described in this paper was carried out on five rabbits. During each session various sensory stimuli were applied to the hind limb of the rabbit and the elicited signals were recorded using the tfLIFEs. Stimuli were, for example, ankle flexion/extension, flexion/extension of one or more toes, and stroking cutaneous receptive fields. The various stimuli were selected as a means to obtain adequate stimuli to activate mechanoreceptors on the paw, and second to localize the activity. Between 50 and 100 g force was exerted during the stroking stimulation to cause some stretching of the skin, but not sufficient to be considered painful. Both the type and the location of stimulation were retained in the experimental record. A similar technique was used by Goodall et al. (1993).

Although the implant location was kept constant between animals, the exact units and thus the sensors recorded by the electrode varied from animal to animal since the units recorded by the electrode are those that happened to be closest to the electrode site after implantation. The analysis conducted was on the activity from the set of units detected. The intent of the study was to obtain a representative set of neural activity given the current state of the art LIFE. The electrode and the implant site were not optimized to obtain the best set of units.

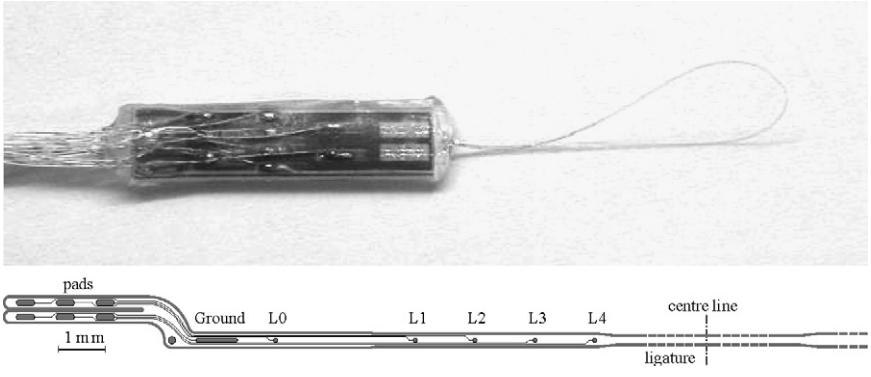

Fig. 1. Picture and unfolded overview of tfLIFE (Hoffmann and Koch, 2005). Total length: 60 mm. Length without pad areas: 50 mm. Each end of the tfLIFE carries a ground electrode (GND), an indifferent recording electrode (L0, R0) and the recording sites (L1–L4, R1–R4).