33rd Annual International Conference of the IEEE EMBS
Boston, Massachusetts USA, August 30 - September 3, 2011

Chronic cuff electrode recordings from walking Göttingen mini-pigs

Mads P. Andersen, Majken Munch, Winnie Jensen, Preben Sørensen and Clemens F. Eder

Abstract—**We present data from cuff electrode recordings from a mixed sensory-/motor nerve as expressed during walking in chronically implanted Göttingen mini-pigs. Our results show that it is possible to filter out residual electromyographic interference and that the energy content of the resulting electroneurographic (ENG) signals modulate clearly with gait. The approach may be used to detect heel strike from cuff electrode measurements to control the timing of stimulation in implantable foot drop correction systems.**

I. Introduction

FOOT drop syndrome is a common complication following cerebral stroke. It affects the patient's ability to raise the toes of the affected foot during walking leading to insecure and slow gait. The disorder can be corrected by electrically stimulating nerves that innervate the dorsiflexor muscles of the foot joint to produce toe lift. Sensing natural neural signals to control assistive devices was suggested a number of years ago by Stein [1], and proved useful to supply reproducible information for feedback purposes in FES systems [2], [3]. Our particular interest lies in the correction of foot drop based on cuff whole nerve recordings as investigated previously e.g. by Haugland [2] and Hansen [4].

Commercially available implantable systems like ActiGait® [5] and Neurostep® [6] stimulate through a cuff electrode placed on the mixed-fiber common peroneal nerve just above the knee joint. Detection of heel strike is essential to control the timing of stimulation. The existing systems rely on external heel switches [5] or electroneurographic (ENG) measurements from an additional implanted electrode around the tibial nerve to detect heel strike [6]. The complexity of these systems can be considerably decreased if it is feasible to detect heel strike from ENG recordings from one mixed-fiber nerve, such that a single cuff electrode can be used for both stimulation and ENG-based heel strike detection [4].

The sensory ENG recordings obtained from a cuff on a mixed nerve may suffer interference from motor ENG targeting the foot muscles and high-amplitude and low-frequency content electromyographic (EMG) signals from nearby muscles during walking. In this paper we present cuff electrode recordings from a mixed nerve as expressed during walking in chronically implanted Göttingen mini-pigs. We discovered that an increase in the lower corner frequency of a high pass filter not only further decreases EMG content, but also affects ENG bursts in different phases of the gait cycle. The purpose of this study was to investigate the spectral characteristics of these cuff electrode recordings during different phases of the gait cycle.

Manuscript received March 25th 2011. This work was supported in part by the Danish Advanced Technology Foundation.

M.P. Andersen, PhD and C.F. Eder, PhD are with Neurodan A/S, Sofiendalsvej 85, 9200 Aalborg SV, Denmark; phone: +45 9933 7226; e-mail: mpa@neurodan.dk.

M. Munch, MSc and Winnie Jensen, PhD are with the Center for Sensory-Motor Interaction, Department of Health Science and Technology, Aalborg University, Denmark.

P. Sørensen, MD is with the Department of Neurosurgery, Aalborg Hospital, Aarhus University Hospitals, Aalborg, Denmark.

II. Methods

A. Implantation

The study was approved by the Danish National Authority for Animal Experimentation ("Dyreforsøgstilsynet"). Two female Göttingen mini-pigs (Ellegaard Göttingen Minipigs A/S, Denmark) were included in the study; both aged 12 months and weighing 21 kg at the entry point in the study.

The mini pigs were trained by clicker-training daily for 2 weeks before implantation to prepare for controlled walking during the measurement sessions.

A dedicated implant was produced for the study as shown in Fig. 1. The implant comprised a four-channel, tripolar cuff electrode (end electrodes connected as in [1]) in silicone with PtIr contact discs (4.5 mm inner diameter, total length 23 mm, 7 mm between the contact discs in the longitudinal direction), connected by a 30 cm MP35N-LT cable to a small, circular, 16-pin connector (NPC16 series, Omnetics Connector Corporation, Minneapolis, MN). The circular connector was partly overmolded with a cone-like "hat" of silicone. The silicone was protected from ruptures by an in-molded Dacron-mesh.

The cuff electrode was implanted on the median nerve of the right forelimb of each pig by an experienced neurosurgeon and the cable was tunneled subcutaneously to a position near the midline of the neck. Here the cable exited percutaneously and the connector was sutured to the skin with four stitches through the silicone "hat". Every four weeks during the study, these sutures were replaced to compensate for daily tear and avoid risk of cable movement and percutaneous infection.

B. Measurement

Measurement sessions were performed twice a week for 90 days after implantation, after which the pigs were euthanized according to protocol. In the present paper we present example recordings obtained from one pig 25 days after implantation.

For the measurement session a hardware system

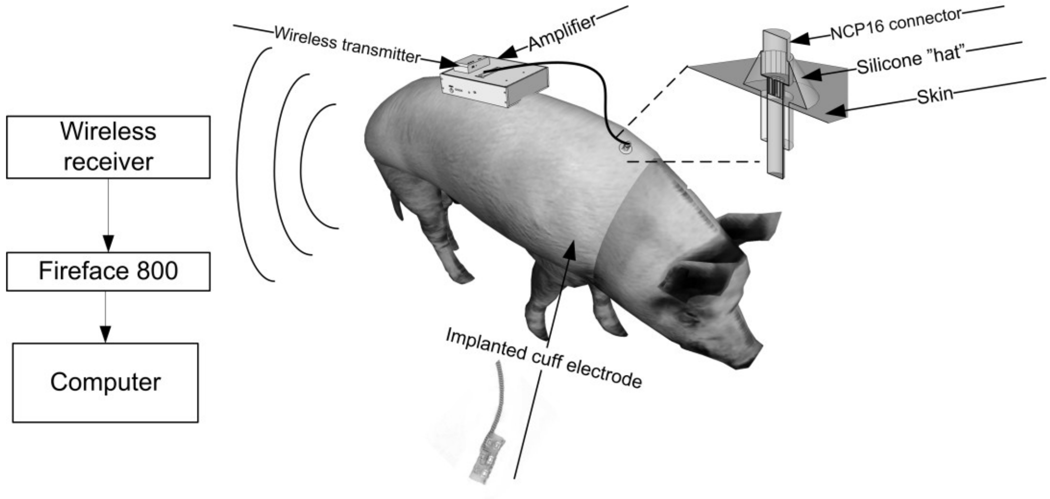

Fig. 1. Measurement setup.

comprising amplifier, AD-converter and wireless transmitter was fitted on the back of the pig and connected to the circular connector of the implant as shown in Fig. 1. Signals were recorded with a custom low-noise, high CMRR custom made amplifier.

A high CMRR of 110 dB at 50 Hz was achieved by providing a bias path without any connection to ground as described in [7]. The overall gain was 70 dB (bandwidth 300 Hz – 20 kHz), and the input referred noise voltage noise density was measured 2.2 nV/√Hz in the present configuration. Amplified signals were transmitted via an E-MU Pipeline wireless audio link (E-MU Systems, Scotts Valley, CA). The regenerated analog signal at the receiver was sampled at 192 kHz using a 24-bit RME Fireface 800 audio interface (Audio AG, Haimhausen, Germany), featuring a dynamic range of 112 dBA. The data was sent to a computer via an IEEE 1394b interface and stored in wave format for later MATLAB import.

Using clicker-training, the pig was directed to follow the instructor by walking at a moderate pace in large circles and treated with a piece of apple for each completed lap. Video recordings were made simultaneously with the ENG recordings to allow for comparison of gait pattern and resulting ENG.

C. Signal processing

The video recording was analyzed to select a segment where the pig was walking straight at a constant, moderate pace without disturbance. Six consecutive gait cycles were chosen and the corresponding cuff electrode recording was extracted for analysis in MATLAB R2010b (MathWorks, Natick, MA).

The power spectral density of the signal was calculated by means of Welch's method with a 1024-point FFT, Hamming window, 8 segments and a 50% overlap.

The signals were filtered using an equiripple FIR filter

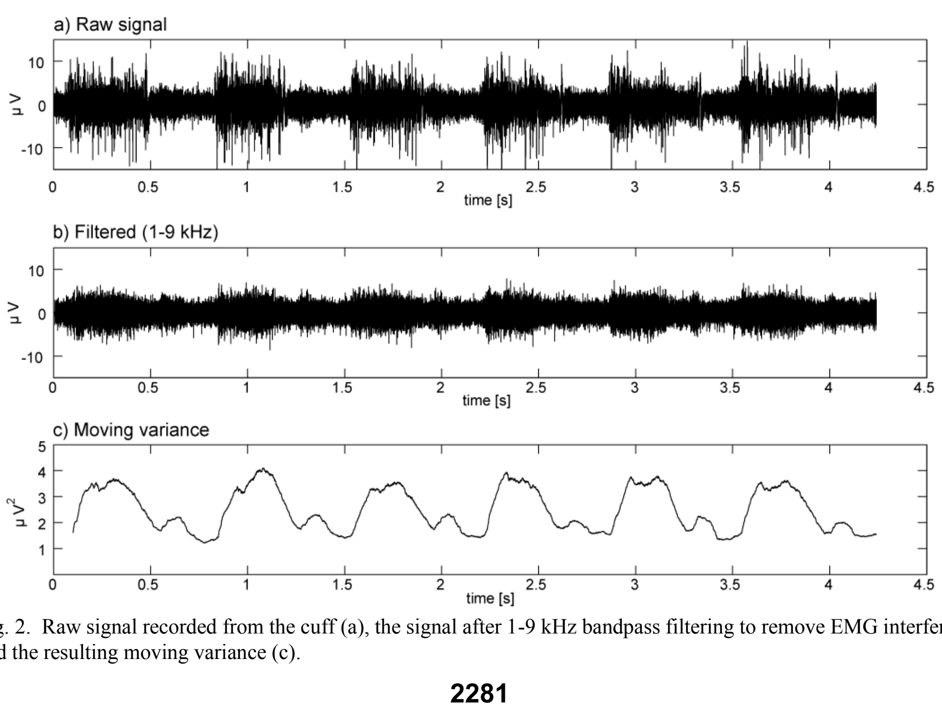

Fig. 2. Raw signal recorded from the cuff (a), the signal after 1-9 kHz bandpass filtering to remove EMG interference (b) and the resulting moving variance (c).

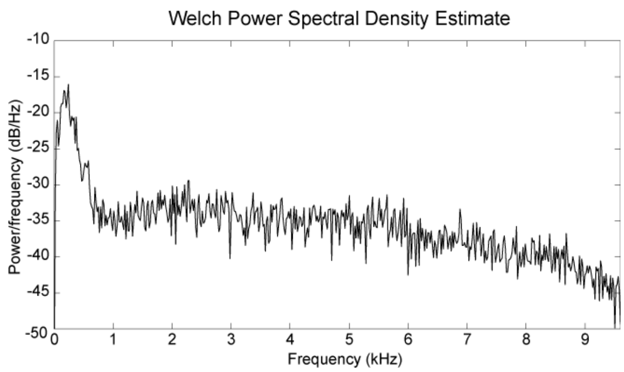

Fig. 3. Power Spectral Density of the raw signal as calculated by Welch's method.

with 200 Hz transition bands, 80 dB damping in the stopbands and varying passbands as described below.

Time-frequency analysis was applied to the signal filtered 1-9 kHz (residual EMG is then considered not to be significant) and a representative spectrogram for a single gait cycle was formed as an ensemble average of individual spectrograms for the six individual gait cycles. The presented spectrogram image was lowpass filtered to produce a smooth, graphical presentation of the average frequency content of a representative gait cycle.

The instantaneous energy content of the signal was evaluated as the moving variance after filtering using a 100 ms sliding window according to (1):

$$Mov\_var_{100}(t) = \frac{1}{N_{100}-1} \cdot \sum_{i=t-N_{100}}^{t} (x_i - \bar{x})^2 \qquad (1)$$

where x_t denotes the filtered signal and N_{100} is the number of samples in a 100 ms segment of the signal.

Moving variance was calculated after filtering with the following passbands: 1-9 kHz, 2-9 kHz, 3-9 kHz, 4-9 kHz, 5-9 kHz, 6-9 kHz, 7-9 kHz and 8-9 kHz respectively. No significant neural activity was expected above 9 kHz. Each moving variance signal was divided into segments corresponding to individual gait cycles (N = 6), the segments were aligned by the first ascending slope and an average moving variance curve was calculated to serve as a representative gait cycle for the filtering configuration in question.

III. Results

Fig. 2 shows the raw signal recorded from the cuff (a), the signal after 1-9 kHz bandpass filtering to remove EMG interference (b) and the resulting moving variance (c), which modulates clearly with gait. The energy content during stance phase is significantly higher than during swing phase.

Fig. 3 shows the power spectral density of the raw signal as calculated by Welch's method. The EMG component below 1 kHz is approximately 15 dB above the ENG signal. Fig. 4 shows the ensemble averaged spectrogram of the six individual gait cycles in the signal after 1-9 kHz bandpass filtering. Synchronized video frames are shown for each phase of the gait cycle: strike, stance, lift and swing. The signal shows content of higher frequency during strike and stance phase than during swing phase, where the activity seems more prominent in the lower frequencies.

Fig. 5 shows the ensemble averaged moving variance curves resulting from filtering with different bandpass configurations.

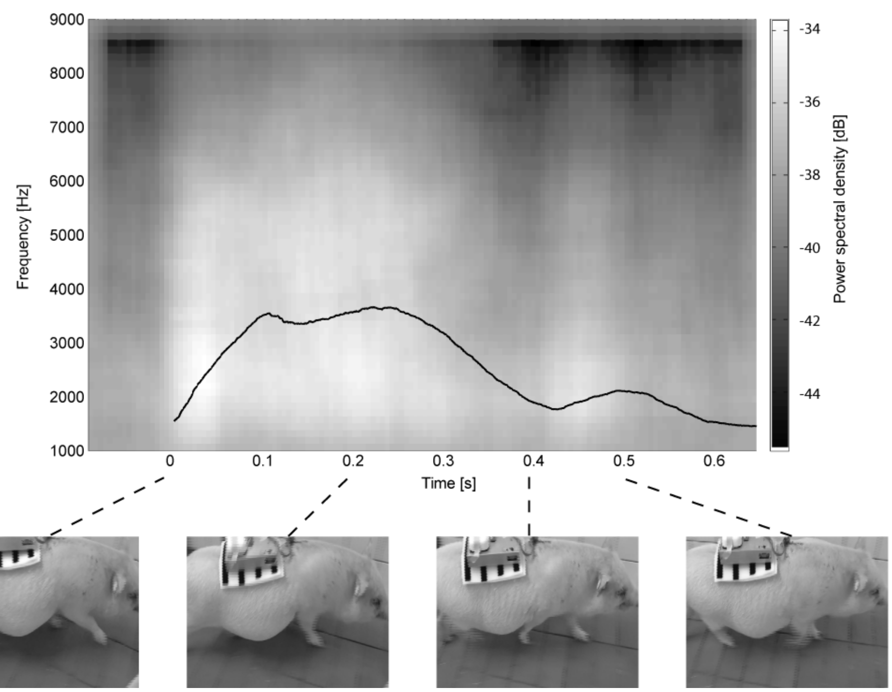

Fig. 4. Ensemble averaged spectrogram of the six individual gait cycles in the signal after 1-9 kHz bandpass filtering. The moving variance pattern is overlaid for comparison. Synchronized video frames are shown for each phase of the gait cycle: strike, stance, lift and swing.

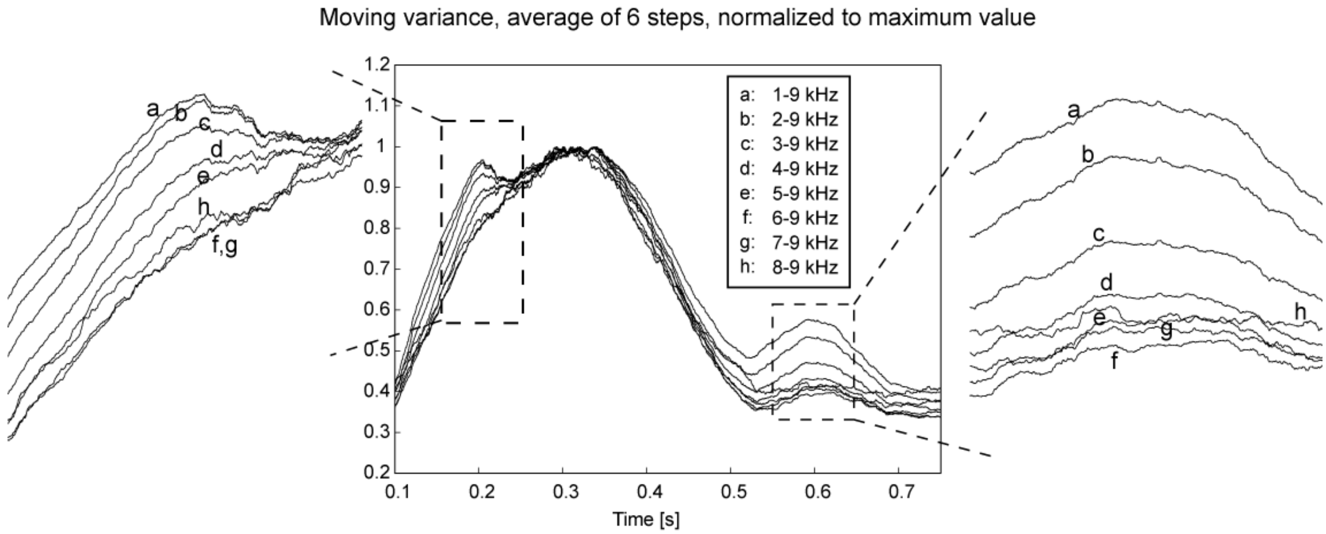

Fig. 5. Ensemble averaged moving variance curves resulting from filtering with different bandpass configurations (a-h). Each curve is the average of six gait cycles and they were normalized in amplitude to have the same maximum for comparison.

Each curve is the average of six gait cycles and they were normalized in amplitude to have the same maximum for comparison. When the band is limited to higher frequencies only, the two smaller bursts around strike and during the swing phase decrease in amplitude relative to the large burst during the stance phase.

IV. DISCUSSION AND CONCLUSIONS

Our investigation shows that it is possible to record high-quality ENG signals from a mixed sensory-/motor pig nerve during walking. A low gain of 70 dB was chosen to allow characterization and filtering of EMG without clipping. We found that the interference could be effectively reduced by appropriate high-pass filtering of higher order.

In previous studies, e.g. Hansen et al. [4], the band width of the signal was reduced significantly to a few hundreds of Hz in the 1-2kHz band, but our results show that - for the same geometric cuff electrode properties - the ENG energy is distributed over a wide frequency range of up to 7 kHz and that the frequency content of the signal is dependent on the gait cycle. This may be explained by the rather short inter-electrode distance of 7 mm. In simulation studies as in [8] it was shown that the spectrum of the simulated transmembrane action potential will depend on the recording configuration and shift its peak to higher frequencies and greater magnitudes with higher action potential velocity. We therefore believe that the observed higher frequency content relates to nerve signals of higher conduction velocity.

We find a clear difference in the total energy content of the ENG activity during stance- and swing phase respectively. This finding indicates that the signals may potentially be used to detect heel strike in a foot drop correction system. The ENG activity found during swing phase is lower in frequency than during stance. The swing phase activity may be filtered out by bandpass filtering in the high frequency area (e.g. 5-9 kHz).

Further investigations will be made to evaluate the quality of the recordings from the entire study period and to investigate the feasibility of the technique for heel strike detection in commercial foot drop correction systems.

ACKNOWLEDGMENT

The authors would like to thank the Danish Advanced Technology Foundation for funding the study, Ellegaard Göttingen Minipigs A/S for teaching the instructors the art of mini pig clicker-training and the staff at the Biomedical Laboratory at Aalborg Hospital for taking good care of the pigs and investigators during the study.

REFERENCES

[1] R. B. Stein, D. Charles, L. Davis, J. Jhamandas, A. Mannard, and T. R. Nichols, "Principles underlying new methods for chronic neural recording," *Can. J. Neurol. Sci.*, pp. 235-244, August 1975.

[2] M. K. Haugland, J. A. Hoffer, and T. Sinkjaer, "Skin contact force information in sensory nerve signals recorded by implanted cuff electrodes," *IEEE Trans. Rehabil. Eng*., vol. 2, pp. 18-28, 1994.

[3] J. A. Hoffer et al., "Neural signals for command control and feedback in functional neuromuscular stimulation: A review, " *J. Rehabil. Res. Dev., 33 (2), pp.* 145-157, 1996.

[4] M. Hansen, M. K. Haugland, and F. Sepulveda, "Feasibility of using peroneal nerve recordings for deriving stimulation timing in a foot drop correction system," *Neuromodulation 6 (1),* pp. 68-77, 2003.

[5] J. H. Burridge et al., "Phase II trial to evaluate the ActiGait implanted drop-foot stimulator in established hemiplegia," *J. Rehabil. Med. 29 (3),* pp. 212-218, 2007.

[6] Hoffer, J.A et al., "Initial results with fully implanted Neurostep™ FES system for foot drop," in *10th Annual Conference of the International FES Society*, Montreal, Canada, July 2005.

[7] E. M. Spinelli, R. Pallas-Areny, and M. A. Mayosky, "AC-coupled front-end for biopotential measurements," *IEEE Trans. Biomed. Eng. 50 (3),* pp. 391-395, 2003.

[8] Donaldson, N., Winter, J., "Multiple-electrode nerve cuffs for low-velocity and velocity sensitive neural recordings," *Med. Biol. Eng. Comput.*, vol. 42, pp. 634-643, 2004.