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In Vivo Localization of Fascicular Activity

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***Abstract*—Users of modern high degree of freedom prosthetics need to provide a large number of natural, intuitive command signals in order to realize the high level of dexterity these devices offer. This level of natural control is beginning to be seen with new technologies like Targeted Muscle Reinnervation; however several serious drawbacks still exist. Flat Interface Nerve Electrode recordings provide a safe and stable means to record natural, intuitive volitional command signals. We investigate the use of Antenna Array techniques to separate command signals from different sources based on their spatial distribution within the nerve. Through a Rabbit sciatic model, it is shown that the system is able to separate compound action potentials elicited from the Tibial and Peroneal branches using 16-channel recordings made on the main sciatic nerve trunk.**

I. INTRODUCTION

Modern prosthetic limbs have far outpaced our ability to use them. These extremely high-tech devices now provide many degrees of freedom, without a natural and robust command mechanism. In order to properly make use of this technology, and advance the quality of life of amputees, it is necessary to develop a set of robust and natural command signals with which users can make full use of these prosthetics. Recently, Targeted Muscle Reinnervation [1] has been shown to provide these kinds of signals, but the surgery required is extremely involved and invasive. Further, the systems require daily electrode placement and have significant cross-talk.

Nerve cuff electrodes have been shown to be both safe and robust means of recording from the peripheral nervous system [2]. Several efforts have been made to use these cuffs to separate recorded signals into the functional components controlling each muscle, using statistical [3, 4], neural network [5] and inverse problem methods [6, 7]. We present a novel method based on Antenna Array techniques [8], where linear weights are used to focus the sensitivity of an array of recording electrodes to the broadband, near-field nerve signal.

II. ALGORITHM

The proposed algorithm is based on antenna array beamforming, where linear weights are applied to individual antenna elements in order to focus the receptive field of the array. Similarly, in this system, weights are applied to each recording contact on a cuff electrode in order to focus the sensitivity to a desired section of the cuff.

A homogeneous model containing no *a priori* assumptions on the geometry and conductances of the nerve, shown in Figure 1, is used to generate a lead field matrix, S, and a simple least squares optimization is used to find the optimal weights for this case. This model consists of a very large saline volume conductor containing a Flat Interface Nerve Electrode (FINE), filled with a simple homogeneous, rectangular epineurium. The least squares optimization is shown in Equation 1, where S is the sensitivity, or lead-field, matrix, t_i is the vector of weights we are looking for, and δ_i is the 2 dimensional delta function corresponding to the ideal sensitivity of 1 at the desired pixel, *i*, and 0 everywhere else.

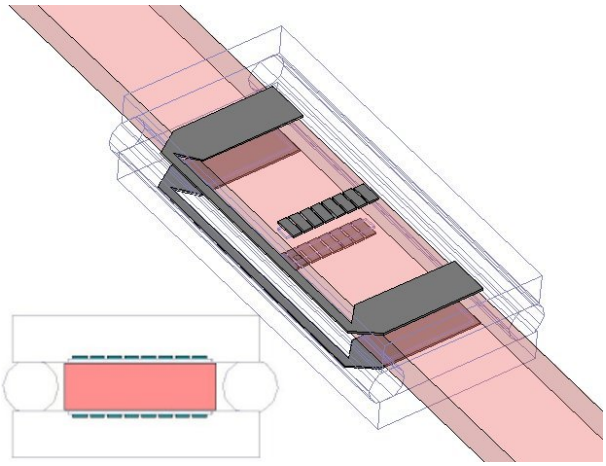

Fig. 1. The a priori model used to generate the Transformation Matrix shown in isometric and transverse (inset) views. The cuff has a 5mm x 1.5mm lumen and 8 recording contacts per side. Recording is performed using a quasi-tripolar technique by referencing the large outer electrodes at the openings of the cuff. Note that this model includes none of the nerve geometry, and so can be solved to generate the lead-field matrix before cuff implantation. The epineurium is shown in pink, and gold foil in grey. The cuff is made of silicone and enclosed in a large saline bath.

For efficiency, Equation 2 is used instead, where Q and R are determined using the QR decomposition of S. Normalization of the resulting weight vectors is as in Equation 3. Once all weights have been determined, they are concatenated into the Transformation matrix T. T can then be applied to a recorded signal, *o*, to produce an estimate, â, of the spatial distribution of the source, as in Equation 4. Once this spatial distribution is known, the relevant weights can be used to separate signals originating

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from different spatial locations, for example from separate fascicles.

$$St_i = \delta_i \quad (1)$$

$$t_i = R \setminus q_i^* \quad (2)$$

$$t_i = \frac{t_i}{\|St_i\|} \quad (3)$$

$$To = \hat{a} \quad (4)$$

III. Methods

A Rabbit sciatic model was chosen due to the ease of surgical access and relatively large size of the nerve, allowing for more spatial variation of the signal over its surface. A 16-contact FINE electrode was fabricated from gold foil on silicone sheeting using techniques similar to [9]. This electrode was placed on the main trunk of the sciatic nerve, and two smaller tripolar cuffs were placed distally on the peroneal and tibial branches, at least 1cm away. Stimulation was performed through these two smaller cuffs at 27 and 22Hz, respectively, in order to generate a combined signal with distinctly separate fascicular sources in the main trunk. Recordings on all 16 contacts of the main electrode were amplified 800x, using the RHA1016 (Intan Tech. LLC) as a preamplifier/multiplexer. These signals were filtered between 300Hz and 5kHz and sampled with 16 bits of precision at 15kHz and then used to attempt to separate the signals.

For initial analysis of the data, the compound action potentials were identified in the raw signal, and the value of all 16 channels at the peak was multiplied by the Transformation matrix. The resulting images were compared to each other, as well as to similar images created at the peak of the stimulus artifact, and from the background noise.

IV. Results

Stimulating the peroneal and tibial branches of the rabbit sciatic nerve, we expect to see compound action potentials (CAPs) from spatially distinct areas in recordings from the proximal main trunk. The beamforming algorithm was applied to recordings of all 16 contacts at the peak of the CAP. The resulting images from each source were compared against each other and against other images from stimulation artifact and background noise.

A typical recording is shown in Figure 2 (top). The stimulus artifact is distinct in terms of both size and duration from the compound action potential, and the image resulting from applying the Transformation matrix at both moments in time is shown next to the trace. Also shown is a randomly selected instant of background noise. Note that all three are distinct. The CAP and artifact images are largely conserved across all trials of stimulation on a given branch.

Comparing CAP peak images for stimulation on different branches gives Figure 2 (bottom). Higher signal in the images indicates a greater estimate of the activity in that pixel. Thus, the images each show a focal, roughly circular source at a distinct spatial position in the nerve cross-section. The lower image seems to predict 2 sources, one slightly weaker than the other, and indeed, other CAPs for this stimulation show high signal at one, the other, or both source locations. Figure 3 shows the reconstructions of the CAP peaks for each branch overlaid onto a histological section of the nerve taken from the experimental position of the electrode. Note that, while the location of the nerve within the cuff is only estimated, it appears to be roughly centered as noted during the experiment. The estimated locations for the two sources match very well to two different fascicle groups. Further histological sections down the length of the nerve have verified that these groups do separate to form the tibial and peroneal branches.

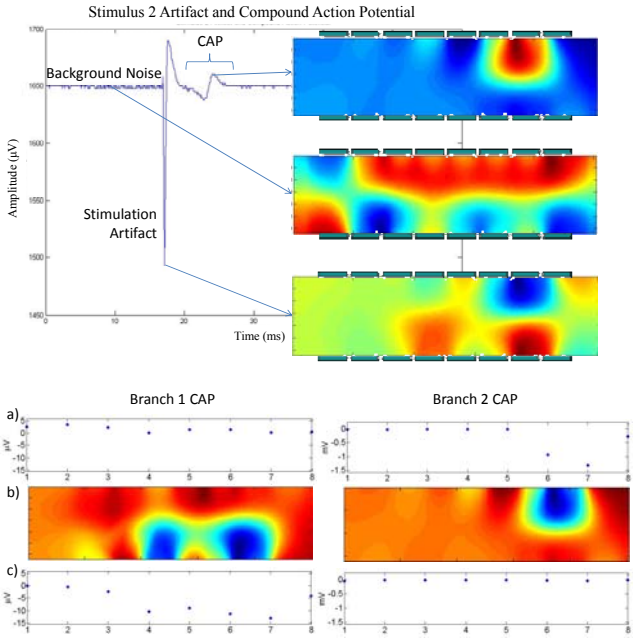

Fig. 2. (Top) (left) Sample evoked potential recording, single channel. (right) Beamforming reconstructions at different instants of the recording: (top) peak of Compound Action Potential (middle) random instant of background noise, (bottom) peak of stimulus artifact. None of the reconstructions are to scale, in order to aid visualization. Note that the spatial signatures are all distinct and the neural activity is focal. (Bottom) a,c) Voltages on each contact at the CAP peak for branch 1 (left) and branch 2 (right) stimuli. The beamforming reconstructions from these voltages are shown in (b). Note that the two appear to be spatially distinct, as expected.

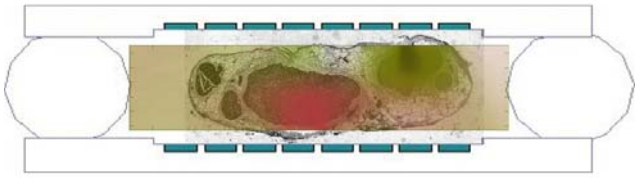

Fig. 3. CAP peak reconstructions overlaid onto a histological cross-section of the nerve. The green (right) overlay is the Peroneal branch stimulation evoked CAP, the red (left) overlay is the Tibial branch stimulation evoked CAP. Note that the full height of the cuff is not included in the reconstruction due to spatial aliasing and noise constraints.

V. Conclusions

Our preliminary in vivo studies show well localized signals from compound action potentials. These signals are qualitatively very different from both background activity and stimulus artifact and are also remarkably spatially distinct from each other. This suggests that the method can be successfully extended to separate signals originating in different fascicular branches, and provide a good command signal for various sets of muscles based on a single cuff implant. Further, comparisons with histology are underway to verify that the estimated locations of the activity correspond to the spatial locations of the fascicles from the given branch. If this is the case, the technique may also be of use in research for mapping fascicles within an intact and living subject.

Acknowledgment

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