ARTIFICIAL CONTROL OF MUSCLE BY ENDONEURAL MULTI ELECTRODE STIMULATION AND SENSING

Wim L.C. Rutten and Raymond L.M. Bouwman

Biomedical Engineering Division, Department of Electrical Engineering, Twente University, P.O. Box 217, 7500 AE Enschede

ABSTRACT

Artificial electrical stimulation of motor nerves for muscle control can be made selective by using intrafascicular micro electrode arrays which contact many individual or small groups of nerve fibres. If at the same time the electrode arrays could record afferent information from the stimulated muscle's spindles and tendon organs, closed loop control of muscles would come into view. This requires 1) research into the possibilities of recording afferent signals, using the micro electrode arrays 2) identification of a stimulated fibre as an alpha motoneuron by evaluation of afferent response patterns. First results are presented.

1. INTRODUCTION

Previous work [1] has shown the capability of micro electrode arrays to stimulate intrafascicularly single motor units. Experiments were performed using twelvefold linear arrys with platinum electrode sites of 10x50 μm, separated by 50 μm, in the peroneal nerve of the rat. As a monitor the isometric twitch force of the EDL muscle was used. For future application in man it is cumbersome or hardly possible to use force monitoring to assess contact with α motor fibres. The use of afferent information from spindles and/or tendon organs, recorded by the same multi electrode as used for the stimulation would be an elegant way for the assessment and thereby also for closed loop control of muscle force. It requires 1) study into the demands for recording of afferent signals 2) design of a stimulation/recognition method which is optimally suited for the identification of stimulated fibres as α fibres.

2. ANALYSIS

2.1 Recording of afferent information

Platinum as an electrode material has the advantage of decreasing impedance with increasing frequency $|Z| \sim 1/f^m$, with m about 0.7. The small contact area of 10x50 μm will however result in a rather high impedance, leading to more equivalent thermal noise.

This thermal noise, with variance $\overline{v^2} = 4\ k\ T\ |Z|\ \Delta f$ volt, must be lower than the afferent extracellular ap amplitudes, which are in the order of 1 μV. Ap bandwidth Δf is about 500-5000 Hz, resulting in a value for $|Z|$ (assuming an rms ap voltage of 1 μV) of at most 21 kΩ at 1 kHz.

In order to minimize unwanted signals a differential electrode recording procedure is preferred. The selectivity of such a dipolar arrangement is set by the decline of measured voltage with distance ~ $1/r^2$, for an isotropic volume conductor and far away (beyond about five times the electrode spacing) from the dipole, or ~ $1/r$ close to one electrode. For a bounded volume conductor (radius smaller than ten times the electrode spacing) the decline will remain less steep than $1/r^2$. Clark and Edell [2] have evaluated several cases for the isotropic, infinite condition. In our case the peroneal nerve bundle has a limited diameter of 500 μm and is isolated from surrounding tissue. With a minimal possible electrode spacing of 50 μm one may expect enhancement of potentials and a more flat fall-off, except close to one electrode (in the order of 25 μm). It can be estimated that one 50 μm dipole, centrally in a 0.25 mm radius bundle will favour recordings from active nearby nodes within a 25 μm sphere.

2.2 Neural network identification

2.2.1 Fibre types and their behaviour

Three types out of the total of efferent α, β and γ and afferent Ia, Ib, II, III and IV fibres can be left out: β, II and IV fibres. β Fibres will be recognized as α or γ fibres, according to their function. About fifty percent of fibres in the bundle is type III and IV Most of them is type IV and is unmyelinated, hence they will be less sensitive to electrical stimulation.
An important difference between fibre responses is to be expected for single pulse versus repetitive pulse stimulation. Single pulse stimulation of Ia, Ib and II fibres will not activate the spinal reflex loop (not enough integrative action) nor evoke antidromic responses.
Single pulse α stimulation of an isometric muscle results in a decremental 'pausing' effect in the firing rate of Ia and II spindle fibres and an incremental 'loading' effect in Ib tendon fibres. Without pre-stretch there will be no afferent effects after γ stimulation with a single pulse.

2.2.2 Sensory partitioning and reflex localisation

Typical numbers of spindles and tendon organs in cat anterior tibial muscle are 64 and 43 respectively on a total of 200 motor units (rat EDL has 40 motor units). Both types of sensors are coupled locally to a limited set of motor units. This 'sensory partitioning' [3] is reflected in the topography of

the nerve bundle: 'reflex localisation'. Afferents and efferents from a specific part of the muscle appear to run close to each other in the bundle. Ia, Ib and II responses, monitored by a 9x9 electrode matrix perpendicular to the bundle, were simulated. Probability for mechanical coupling factor k was assumed to obey reflex localisation and to be dependent on distance d between central and recording electrode in a $\exp(-d^2)$ fashion. The response is a change Δr in the discharge rate from the rest value r_0 according to $\Delta r = k\, r_0$. A certain randomness was added to r_0, k and the exponential relationship. An electrode-fibre connection density of 0.5 was assumed.

A three layer perceptron network with back propagation as learning rule was trained by simulated α and non-α responsepatterns (5000 each). The network had 81 inputs (9x9 electrodes), 40 nodes in the first layer, 13 in the second and 1 output node (it classifies the fibre as α or non-α type). Normal noise N was added to responses Δr with a SNR defined by $SNR = 10 \log [\Sigma \Delta r_i^2 / \Sigma N_i^2]$ (dB). The learning process was evaluated by calculating a RMS error (after P patterns): $RMS = \sqrt{\Sigma_{p=1,P}\, 1/P\, (d_p - o_p)^2}$ in which d_p is the desired output for pattern p and o_p the actual output. Four different sets of patterns were generated, each set containing 10000 responses. Each set was applied twice.

3. RESULTS

3.1 Recording of afferent information

Typical impedances $|Z|$ of platinum electrodes in the array appeared to be about 30 kΩ at 1 kHz, resulting in a thermal noise which is just acceptable for ap recording (see above). To improve recording quality, 50-100 times response averaging was applied.

Figure 1 shows some results of selective recording of afferent information in the peroneal nerve of the rat in response to mechanical stretch of the EDL muscle. A mixture of spindle and tendon responses is to be expected since muscle length is not constant. Also shown is the compound ap response recorded by a bipolar hook electrode around the same nerve. Several firing complexes after stimulus onset and offset can be seen. Also, response complexes at different electrode pairs differ in shape and amplitude, thereby demonstarting selectivity.

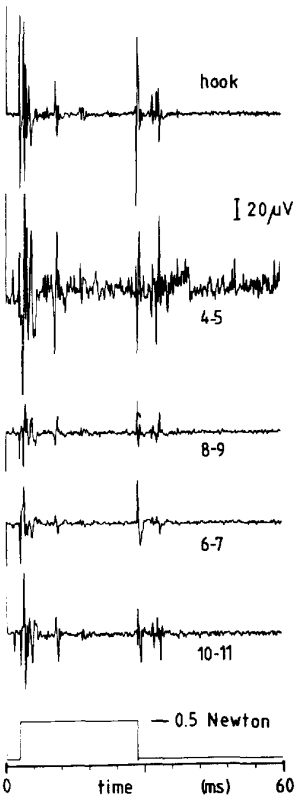

Figure 1. Bipolar recordings using a bipolar hook electrode around the nerve (top) and 4 electrode pairs in the nerve. The four pairs belong to a twelve-fold linear array in silicon technology (electrode spacing 50 μm [1]). Recordings were made in the peroneal nerve of the rat in response to an on-off stretch of the EDL muscle (bottom). The stimulator gives short artefact peaks at onset and offset.

3.2 Neural network identification

Figure 2 shows the RMS error during training as a function of SNR. The four trained networks were evaluated with 10 'recall' sets of 500 α responses with SNR values between 8.3 and 34.4 dB and with 10 sets of 500 non-α responses. Detection probabilities $P(0|0)$ and $P(1|1)$ were calculated. As the aim is to identify α motoneurons for selective stimulation, misclassification of a non-α response is worse than not recognising an α-response. It appeared that for 90 percent detection of α responses a network that has learned with a SNR of about 20 dB will satisfy. It will correctly identify non-α responses in never seen patterns in which SNR is 20 dB.

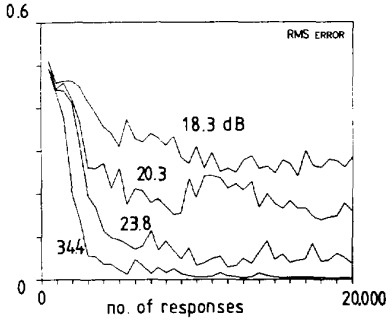

Figure 2. RMS error during training of neural network for SNR's in the range 18.3 and 34.4 dB.

4. REFERENCES

[1] RUTTEN, W.L.C., VAN WIER, H and PUT, J.H.M., 1991, Sensitivity and selectivity of intraneural stimulation using a silicon electrode array. IEEE Transactions Biomedical Engineering 38, 192-199.

[2] CLARK, L.D.and EDELL, D.J., 1987, Electrode spacing considerations for neural signal transducers, Proc. Ninth IEEE/BME conference Boston, p. 1660-1661 and Eleventh conf Seattle p.1751-1752.

[3] CAMERON, W.E., BINDER, D.B., BOTTERMAN, B.R., REINKING, R.M., and STUART, D.G. "Sensory partitioning" of cat medial gastrocnemius by its muscle spindles and tendon organs. J.Neurophysiol.46:32-47, 1981.