On-line Joint Angle Estimation Based on Nerve Cuff Recordings from Muscle Afferents

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Abstract. ***Objective:*** *In order for muscle afferent recordings to be useful as sensory feedback in closed-loop FES applications, a reliable feedback signal has to be available. We examined whether an artificial neural network (ANN) could be used to estimate joint angle from muscle afferent recordings.* ***Methods:*** *The electroneurograms (ENG) of the tibial and peroneal nerve branches were recorded using nerve cuff electrodes in six acute rabbit preparations. The rabbit's ankle joint was rotated using ramp-and-hold profiles. The Lateral Gastrocnemius (LG) or the Tibialis Anterior (TA) muscles were stimulated using intramuscular wires. The joint angle was predicted from muscle afferent recordings using an ANN. To improve the on-line joint angle estimation it was attempted to pre-tune the tibial and peroneal signals and re-train the ANN with these pre-tuned data.* ***Results:*** *The mean prediction error was less than 2.0° when the ENG signals were pre-tuned and the ANN was re-trained with these pre-tuned data.* ***Discussion:*** *It was possible to use ANN's to predict joint angle from muscle afferent recordings. We compensated for the high inter-rabbit variability when the ENG signals were pre-tuned and the ANN were re-trained with these data. Thus it is suggested, that nerve cuff recordings of muscle afferents are applicable as natural sensory feedback in closed loop control.*

Keywords – muscle afferents, nerve cuff, peripheral nerve, closed-loop control, sensory feedback

1. Introduction

Functional electrical stimulation (FES) has demonstrated to be a useful technique to restore motor function of paralyzed limbs. Also, it has been demonstrated that intrafascicular recordings of muscle afferents from non-stimulated muscles were useful as sensory feedback in single-channel, FES closed-loop control of the ankle joint position in cats [1]. In the present study we examined whole nerve cuff recordings of muscle afferents to evaluate whether the recordings can be used as feedback. Group Ia, group Ib and group II afferents originate from the muscle spindles and the Golgi tendon organs. Afferent responses from group Ib afferents are believed to carry an estimate of muscle force [2]. Group Ia afferents mediate both static and dynamic sensitivity of the muscle (muscle length and velocity) whereas group II primarily mediates static sensitivity [3]. Previous studies showed that nerve cuff recordings of muscle afferents mainly contained information about joint angle and joint torque even though non-linear behaviour was observed and there was a large inter-rabbit variability [4], [5]. A neuro-fuzzy model has been used to map the non-linear relation between the muscle afferent responses and joint angles [6]. The objective of the present work was to investigate whether an artificial neural network could be used to predict joint angles. It was further examined which factors could secure reliable, *on-line* joint angle estimation.

2. Methods

The Danish Committee for the Ethical Use of Animals in Research approved the experimental procedures. Six acute experiments were performed using female New Zealand rabbits. The anaesthesia was initiated with 2.0 mg/kg Midazolam (Dormicum^{TM}). Intramuscular injections were repeated every 20 minutes to maintain the anaesthesia (0.095 ml/kg Fetanyl and 0.30 mg/kg Fluranison, combined in Hypnorm^{TM}). Tripolar nerve cuff electrodes were implanted around the tibial and peroneal nerve branches in the rabbit's left hind limb (cuff length = 22 mm, inner diameter = 2 mm and 1.8 mm). The sural nerve was cut distal to the tibial cuff to minimize afferent activity from the cutaneous receptors. The nerve signals were pre-amplified and filtered before being sampled (gain range = 200,000 - 1,000,000, 2nd order filter, F_{hp} = 500 Hz and F_{lp} = 5 kHz, F_s = 10 kHz). The ENG signals were rectified, bin-integrated over 12.5 ms windows and low-pass filtered at 10 Hz. In part of the data set used for training the ANN's intramuscular stimulation was applied either to the LG or the TA muscles (80 Hz stimulation, recruitment levels = 25%, 50% or 100% of maximum force, wire diameter = 0.1 mm, active area = approx. 3 mm, separation between wires = 2-3 mm,). Stimulation artefacts were blanked out by only integrating the ENG signals over a 9 ms artefact-free window occurring between the artefacts. The rabbit's ankle joint was rotated according to a ramp-and-hold profile (ramp velocity = 20°/s, excursion = 20°, duration of hold plateau = 2 s, initial position = 100°). The first ANN was trained using data from joint flexion (80°-100°, referred to as the *flexion-ANN*). The second ANN was trained using data from joint extension range (100°-120°, referred to as the *extension-ANN*). The ANN's had four input neurons (tibial and peroneal ENG, one-sample delayed tibial and peroneal ENG), 20 hidden layer neurons and one output neuron (target angle). The ANN was a recurrent network, trained using backpropagation through time Data from three rabbits were selected to constitute the two training sets. The ANN's were tested with data from the three remaining rabbits, referred to as R1, R2 and R3 (*Test I*). To determine which properties could improve the on-line joint angle estimation we used two tests (*Test II and Test III*). A part of the test data were first used to calculate pre-tuning factors for the ENG signals (the mean values of test data were scaled to match the mean value of the original training data) and to re-train the flexion-ANN and the extension-ANN. The effect of pre-tuning the tibial and peroneal ENG signals were then tested with the remaining part of the test data using the originally trained ANN's (*Test II*). The effect of re-training the ANN's with the pre-tuned data were examined in the third test performed (*Test III*).

3. Results

The joint angle was predicted from the muscle afferent recordings using the flexion-ANN or the extension-ANN in a simulated on-line session. The mean and maximum absolute errors are given in Table 1. It was observed that the predicted joint angle from the originally trained ANN's (*Test I*) followed the approximate shape of the target angle, but there were large deviations. A clear improvement was found when the pre-tuned data were used to predict the joint angle (*Test II*). The best fit was found when the ANN's were re-trained with pre-tuned ENG signals from new rabbits (*Test III*). In Test III the mean errors were 2.0° and 1.5°.

Table 1. Mean and max absolute errors between target and estimated joint angle. *Test I:* Originally trained ANN. *Test II:* originally trained with pre-tuning ENG signals. *Test III:* ANN re-trained with tuned ENG signals. No results are given for the training set of Test III, since an ANN was trained for each of the three rabbits.

Error		*Test I*		*Test II*		*Test III*	
		Mean	*Max*	*Mean*	*Max*	*Mean*	*Max*
	Train	3.0°	16.2°	3.0°	16.2°	-	-
F	*R1*	20.9°	41.1°	10.0°	23.2°	1.6°	17.6°
L	*R2*	8.5°	23.1°	4.1°	19.4°	1.8°	14.1°
E	*R3*	6.7°	47.3°	6.5°	40.5°	2.6°	21.3°
X	*Mean*	**12.0°**	**37.1°**	**6.9°**	**27.7°**	**2.0°**	**17.6°**
	Train	2.3°	9.0°	2.3°	9.0°	-	-
E	*R1*	17.4°	35.4°	5.2°	14.3°	1.2°	6.0°
X	*R2*	7.3°	22.7°	5.2°	13.6°	1.1°	8.7°
T	*R3*	4.0°	33.3°	3.4°	15.2°	2.3°	21.8°
	Mean	**9.6°**	**30.5°**	**4.6°**	**14.3°**	**1.5°**	**12.1°**

4. Discussion and Conclusions

In this study we evaluated whether sensory information could be extracted from nerve cuff recordings of muscle afferents, and we examined which factors were important to secure a reliable, on-line joint angle estimation with new rabbit data. Two ANN's were trained to extract joint angle from two different areas of the physiological joint range, because it was observed that the peroneal ENG response in the joint flexion range and the tibial ENG response in the joint extension range were low. We demonstrated that it was possible to extract joint angle from muscle afferent recordings on-line. This was possible for all three rabbits tested. The results indicate that the method proposed in this study could secure reliable, on-line joint angle estimation and compensate for the inter-rabbit variability. The ANN re-training and the pre-tuning of the ENG signals were in all three rabbits done within the timeframe of one hour. This short timeframe are realistic for both acute and chronic applications. Thus, it is suggested that nerve cuff recordings of muscle afferent signals can be useful as sensory feedback in a closed-loop controlled FES system if the ENG signals and the ANN's are submitted to rabbit specific pre-tuning.

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