OBTAINING SKIN CONTACT FORCE INFORMATION FROM IMPLANTED NERVE CUFF RECORDING ELECTRODES

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ABSTRACT

This study aimed to investigate how the electrical activity in a cutaneous nerve relates to the force applied on glabrous skin. Nerve cuff electrodes implanted on the tibial nerve of cats were used to record the electroneurogram (ENG) when the footpad was probed by a servo-controlled motor. The ENG signal was non-linearly dependent on the applied force, it saturated for high forces, adapted when constant forces were applied and was very sensitive to "slippage." Linear system identification techniques provided estimates of force that were only accurate for limited ranges of force amplitude and frequency. Improved estimates were obtained using a real- time, analog, non-linear filter that included proportional, integral and exponential terms. Accurate estimations of input force could best be made if the force was not constant but varied in the 0.1-5 Hz range.

Cuff electrodes implanted on nerves supplying glabrous skin of the hands or feet may provide feedback suitable, for example, for the closed-loop control of functional electrical stimulation (FES) of paralyzed muscles in spinal cord injured patients.

INTRODUCTION

In the intact organism, the central nervous system uses **sensory feedback** information from specialized sensors in the skin, muscles and joints to continuously regulate its motor output. It has been proposed [5,7,8] and shown for spinal cord-injured subjects in pilot experiments [3] that **closed-loop** control of FES using feedback from force and position sensors can significantly improve performance while reducing user dependence on visual monitoring. Control of stance and gait by paraplegics can also be improved by using sensors to provide feedback on load distribution on the soles of the feet [2,4]. Practical implementation of closed-loop control of FES will require **implantable sensors** [see 1,5,12] and **real-time** signal processors. We show here that implanted **nerve cuff electrodes** can be used to record the activity generated by axons in a sensory nerve, arising mainly from skin mechanoreceptors, and that **real-time, non-linear analog processing** of the recorded electroneurogram can provide an accurate dynamic prediction of skin contact force.

METHODS

The cat footpads served as a model of human glabrous skin. Six cats were surgically implanted with a 30 mm long, 2.5 mm I.D. silicone rubber cuff with 3 circumferential stainless steel electrodes (Cooner AS 631) on the left tibial nerve, proximal to the ankle joint. "Balanced tripolar" differential recording at a gain of 20,000 and 1-10 kHz bandpass reduced pickup of unwanted EMG and other sources of noise [6].

Data collection: Under halothane gas anaesthesia, the cat's left foot was secured and a servo-controlled linear motor with a 1 cm disc-shaped probe was used to impose mechanical deformations on the central footpad. The applied force was monitored with a transducer in series. Motor position and compliance were electronically regulated with position, velocity and force feedback. Control signals included sinusoidal or triangular oscillations at 0.1-10 Hz of varying amplitude, and series of steps. The tibial ENG was rectified and integrated in 10 ms bins (Bak PSI-1). Analog processing of tape-recorded signals, digitization and analysis with an IBM compatible '386 computer were done off-line.

Linear signal analysis: The impulse response (**IR**) relating rectified ENG and force was identified in a window from -0.5 s to 1.0 s using the two-sided linear filter identification method of Hunter and Kearney [9], for a variety of tasks and data epochs. An estimate of force was obtained by convolving the IR with the ENG. The cross-correlation for zero time delay between measured and estimated force ($\mathbf{R^2}$) was used to quantify the accuracy of the estimate.

Non-linear, real-time, analog signal processing: The rectified and bin integrated ENG signal was processed through a real-time analog filter that included proportional, integral, differential (**PID**) and exponential (**EXP**) terms (**Fig. 1**). Global filter time constants, gains and offsets were determined off-line by visual comparison of oscilloscope displays of the filter output and the force. The filtered ENG was then digitized and subjected to the same identification method used for the bin-integrated ENG and force (see above).

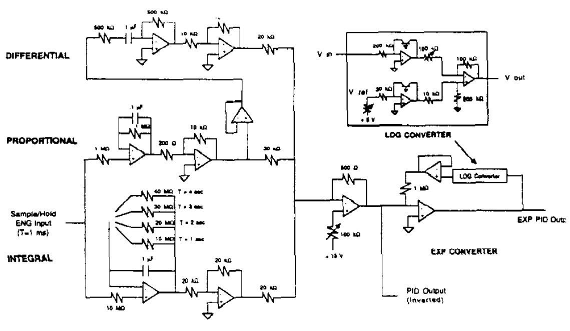

Fig. 1. Analog filter circuit diagram.

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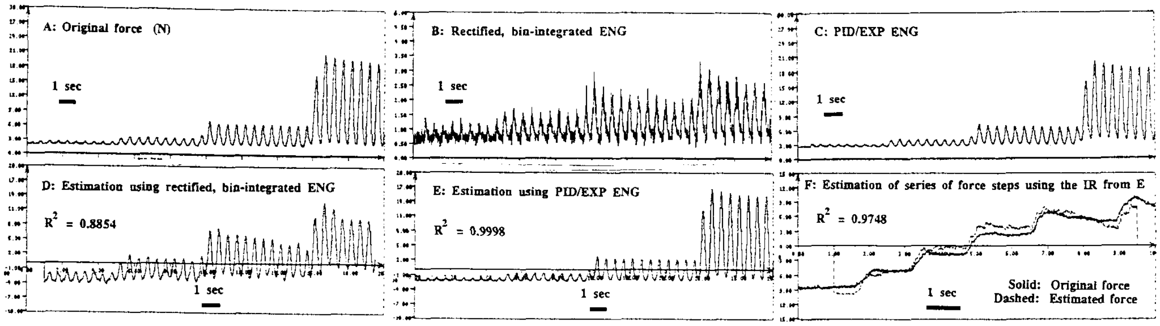

Fig. 2.

RESULTS AND DISCUSSION

Fig. 2A shows the force applied to the cat footpad in an experiment where the command signal to the motor was a 2 Hz sine wave of increasing amplitude. **Fig. 2B** shows the ENG signal recorded from the tibial nerve, rectified and bin-integrated. The ENG was modulated in phase with the force but over a narrower amplitude range. The computed IR, convolved with the ENG from **Fig. 2B**, gave the **estimated force** shown in **Fig. 2D**. This estimate did not predict well the amplitude of the force. Also, the amplitude of successive peak and baseline values tended to drift more than the input force.

Considerably better predictions of force were obtained when the recorded ENG signal was processed through the **real-time, analog PID/EXP filter** described in **Fig. 1**. **Fig. 2C** shows the output of the PID/EXP filter for the **same** ENG data shown in **Fig. 2B**. Using the IR given by the linear filter identification method when the PID/EXP ENG was used as input, the estimation of force was excellent (**Fig.2E**). The same IR was also used to estimate very different force inputs; e.g., in **Fig. 2F**, it was convolved with the PID/EXP version of the ENG recorded during a series of force steps.

There are several reasons for the poor force amplitude estimation using linear filter identification analysis based on the rectified ENG. First, maintained forces were inconsistently replicated in the raw ENG due to receptor adaptation [10]. Second, an **off-response** could occur, in the wrong direction, if the force suddenly declined from a low level to zero; this effect is probably related to a **slippage signal** generated by phasic mechanoreceptors when glabrous skin is deformed in either direction as force declines [11]. Third, these data are clearly not stationary and the method assumes stationarity [9]. Fourth, the ENG/force relation is clearly non-linear, especially for the higher forces reached (up to 40 N) and this method assumes linearity. The output of the PID/EXP filter (**Fig. 1**) helped reduce the non-linearities in the raw ENG/force relation, prior to using the linear filter identification approach. However, the output of the PID/EXP processor was sluggish when following suddenly declining forces, a consequence of using analog components. **Digitally** implemented **nonlinear** approaches may offer better performance for practical applications.

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