Estimation of surface electromyogram spectral alteration using reduced-order autoregressive model

S. Karlsson¹  J. Yu²

¹Department of Biomedical Engineering & Informatics, University Hospital of Northern Sweden, Umeå, Sweden
²Department of Forest Resource Management & Geomatics, Swedish University of Agricultural Sciences, Umeå, Sweden

Abstract—A new method is proposed, based on the pole phase angle (PPA) of a second-order autoregressive (AR) model, to track spectral alteration during localised muscle fatigue when analysing surface myo-electric (ME) signals. Both stationary and non-stationary, simulated and real ME signals are used to investigate different methods to track spectral changes. The real ME signals are obtained from three muscles (the right vastus lateralis, rectus femoris and vastus medialis) of six healthy male volunteers, and the simulated signals are generated by passing Gaussian white-noise sequences through digital filters with spectral properties that mimic the real ME signals. The PPA method is compared, not only with spectra-based methods, such as Fourier and AR, but also with zero crossings (ZCs) and the first AR coefficient that have been proposed in the literature as computer efficient methods. By comparing the deviation (dev), in percent, between the linear regression of the theoretical and estimated mean frequencies of the power spectra for simulated stationary (s) and non-stationary (ns) signals, in general, it is found that the PPA method (devₚₐₚ = 4.29; devₚₐₙ = 1.94) gives a superior performance to ZCs (devₚₛ = 8.25) and the first AR coefficient (devₚₛ < 4.18 < devₚₐₚ < 21.8; 0.98 < devₚₐₚ < 4.36) but performs slightly worse than spectra-based methods (0.33 < devₚₛ < 0.79; 0.41 < devₚₐₙ < 1.07). However, the PPA method has the advantage that it estimates spectral alteration without calculating the spectra and therefore allows very efficient computation.

Keywords—Myo-electric signal, Electromyography, Mean frequency, Autoregressive model, Pole phase angle, Spectral alteration

1 Introduction

Analysis of the frequency spectra of myo-electric (ME) signals is a commonly used method to determine local muscle fatigue and has attracted great interest in the research fields of rehabilitation medicine, ergonomy and sports physiology. Moreover, it has been used in determination of force production (BASMAJIAN and DE LUCA, 1985; BIGLAND-RITCHIE, 1981; DE LUCA, 1997), ME signal conduction velocity (BASMAJIAN and DE LUCA, 1985; HÄGG, 1992; LINDESTROM and MAGNUSSON, 1977), muscle fibre conduction velocity (GERDLE and FUSGI-MEYER, 1992; KUPA et al., 1995; WRETLING et al., 1987) and in diagnostic classifications (INBAR and NOUJAIM, 1984).

It is well known that the power spectral density function (PSD) of the surface ME signal undergoes progressive compression and change of shape during sustained contractions (MERLETTI and LO CONTE, 1995). There are two major components of the ME signal that can effect the PSD (recording factors excluded): firing behaviour of the motor units (MUs) in the low-frequency region (5–40 Hz) and the shape of the motor unit action potentials (MUAPs) above 40 Hz. The shape of the MUAPs is highly dependent on muscle fibre type and diameter, number of active MUs, number of muscle fibres in active MUs, mean and distribution of muscle fibre conduction velocity, blood flow, ion concentration and pH. For reviews, see BASMAJIAN and DE LUCA (1985), DE LUCA (1979), KARMEN and CALDWELL (1996), and MERLETTI et al. (1992).

During sustained voluntary contractions, MUAPs are almost asynchronous, and the resulting ME signal detected at the surface of the skin can be considered as a band-limited stochastic process with Gaussian distribution of amplitude and zero mean (DE LUCA, 1979; BASMAJIAN and DE LUCA, 1985; LINDESTROM and MAGNUSSON, 1977). The most widely used method for estimating the PSD of the ME signal is the Fourier transform, because of the extremely computationally effective fast Fourier transform (FFT) algorithm. However, spectral estimates based on the Fourier transform are affected by the phenomena of frequency leakage (related to pre-windowing), frequency resolution (related to the stationarity problem and selection of time segments), large estimation variance and the assumption of signal periodicity or signal equal to zero outside the analysis segment.
Parametric (e.g., autoregressive (AR)) identification methods reduce these problems. These methods are specifically useful when short data segments are available owing to time-varying (non-stationary) ME signals, e.g., during dynamic (isokinetic) contractions. In fact, these methods extrapolate the values of the autocorrelation for lags greater than the analyzed segment length.

GRAPE and CLINE (1975) proposed the autoregressive moving average (ARMA) method to analyze the ME signal and were able to separate several different limb movements for prosthetic control. Later, PAISS and INBAR (1987) investigated the validity of the AR model in the spectral domain by monitoring the change in the AR prediction and reflection coefficients in the time domain during fatigue. Their results suggested that the first prediction, reflection coefficient and the normalized energy of the error of the AR model declined with time during local fatigue. They also investigated the positions of poles, but concluded that they could not be plotted against time, because the poles are complex and not ordered in a time index.

KIRYU et al. (1994) investigated the time-varying behavior of the AR parameters of an ME signal detected during a linear force increasing contraction. They investigated the reflection coefficients, the AR model spectrum and prediction errors. They found that the spectrum of newly recruited motor units differed from that of the rest of the ME signal.

The main problem with the parametric modeling methods, including the AR and ARMA methods, is the selection of the model order and interpretation of the parameters. In applications where only the general shape of the PSD is required (for example estimating muscular fatigue) an AR model of order 2-7 is enough, but if spectral peaks such as the firing rate of dominant MUs are also of interest, a model of order at least 25 is needed (PAISS and INBAR, 1987). In 1985, KUC and LI showed that the center frequency of a narrow-band and discrete-time process, such as a reflected ultrasound signal, can be estimated from the parameter values of a reduced (second-order) autoregressive model.

Later, SALTZBERG et al., 1985; SALTZBERG, 1986) introduced a method of representing the spectral moments of band-limited signals, without computing the Fourier transform, as weighted sums of samples of the autocorrelation function (ACF). This method was then modified by MURLETTI et al. (1995) to allow even faster convergence and adjustable sensitivity to noise (or signal) in the high-frequency portion of the PSD (350-500 Hz).

The objective of this paper is to study the possibilities of using a lower-order (second) AR model to estimate the mean frequency (MNF) of the PSD to track the spectral alteration during muscle fatigue. This model gives only one complex pair of poles that can be investigated against time. Moreover, the first prediction and reflection coefficients proposed by PAISS and INBAR (1987) were also considered for the MNF estimate. Both block-by-block-based (the data sequence divided into individual segments) and adaptive estimation methods were investigated. The latter method is furthermore suitable for on-line tracking of spectral alteration.

To validate the AR method, both simulated ME signals and real ME signals from six healthy subjects during sustained isometric knee extensions at 70% MVC were investigated and compared with the Fourier method. The simulated signals were produced by passing white noise through IIR filters, giving signals with spectra similar to real ME signals.

2 Methods

In this paper, we propose to estimate the value of mean frequency by fitting a second-order AR model to the input signal and then using the phase angle of the symmetric poles.