A Method for Signal Quality Assessment during Ambulatory EMG Recording

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Abstract

Biopotential signal recording is often affected by noise during recording. There is a large body of literature on noise removal techniques for every class of biopotential signals. However, obtaining clean recording is preferable to cleaning a noisy recording. An instantaneous quality measure of the signal to noise ratio during recording would be invaluable in correcting a defective recording situation. Such a quality measure can be used to correct the situation immediately. Ambulatory EMG recording to study complex muscle movement is one such situation where the quality of recording can easily deteriorate when electrodes become loosened or wires break due to entanglement with the subject's moving body.

We propose a model based approach for EMG quality assessment in the presence of most common types of noise. The method has been tested on simulated and real EMG sequences in the presence of numerically synthesized as well as experimentally induced noise. The method is amenable to implementation on line using a low cost microcontroller which could be easily included as a small circuit attached to the preamplifier.

Key Words

EMG, on-line monitoring, Signal quality assessment, Sequential Least Squares, whitening filter, whiteness test.

1. Introduction

Recording the electromyogram or EMG during complex muscle movement is an important tool in studying neural control of the musculoskeletal system. For example, multichannel ambulatory EMG is regularly used in gait analysis for both experimental and clinical investigations. In such EMG recording, the principal sources of noise are, (i) motion artefact, (ii)high frequency noise from electronic systems, (iii) power line interference at 50Hz or 60Hz, along with harmonics which are generated due to non-linearity in the transmission path, and (iv) unwanted biological signal like the EEG or ECG [1].

Despite several precautions taken before the actual recording, the EMG signal may become noisy during the recording itself [4]. Although later offline filtering can solve the problem in some cases, it may often be desirable to terminate the recording and correct the problem before proceeding. The signal-to-noise ratio of a recorded biological signal depends on the definition of the signal. Unlike signals like the cardiogram which are fairly regular, the EMG is a stochastic signal that can only be described in a statistical sense. In the absence of other information, the most well known characteristic of the EMG signal is the spectral shape [2], [3]. The characteristic spectral shape or its equivalent time domain description can be used to recognize the EMG.

In this paper, we present a model based method for assessing the quality of EMG in the presence of common types of noise, particularly, wideband noise, and powerline noise.

2. Methods

Characteristic spectral shape can be used to identify the presence of EMG. Shape characterization of the spectrum may require a pattern matching method, in addition to the spectrum estimation. Alternatively, equivalent time domain AR parameter estimation can be done and the AR coefficients can be classified as due to EMG or noise. Both these methods are computationally expensive. A variation of the above methods is to determine a matched filter using typical AR coefficients for the EMG. A reasonably small AR model is sufficient to model surface EMG [5]. These AR coefficients will depend on the recording electrode geometry as well as the muscle.

Design of Adaptive Matched Filter:

Since the major application of the proposed method is to develop an online assessment system that can be used for analyzing recorded ambulatory EMG, the EMG can be safely assumed to be wide sense stationary. This permits us to model the EMG signal using an AR model given by-

$y(n)=a_1y(n-1)+a_2y(n-2)+a_3y(n-3)....a_k(n-k)+w(n)$ where
n:- discrete sampling instants.
y(n):- value of signal at time t = nT
w(n): - random white noise
T=sampling period
In this case, k=6 i.e. 6^{th} order model is used.

Programs were written in C as well as MATLAB which use the Algorithm of Sequential Least Squares (SLS) to determine these coefficients. The AR coefficients were determined for the EMG recorded from a few hand muscles at different times. A 6^{th} order model was chosen because the values of the higher order coefficients were very small. If the generating mechanism is of order k, the SLS algorithm recognizes this and makes the higher order coefficients zero [5]. The AR model converged well and the coefficients for all the muscles were similar. If the values are very different, then the specific coefficients for that muscle must be used, otherwise the average coefficient values can be used.

The method uses a single Whitening filter, designed using the AR coefficients of the EMG. This filter has an impulse response that is the inverse of the AR matched filter i.e. if the AR matched filter has a frequency response G(w), the whitening filter has a frequency response 1/G(w). A maximum limit on the amplitude of the whitening filter has been set, to avoid overflow error in case the AR matched filter has an amplitude response that is very low at certain frequencies.

According to the construction of the whitening filter, when an EMG signal is applied as an input to the whitening filter, the output should be white. On the other hand, if any other signal that has a spectrum shape not similar to that of the EMG signal is applied as input, response will be non-white. Thus, from the quality of 'whiteness' of the output signal, the quality of the EMG signal can be determined.

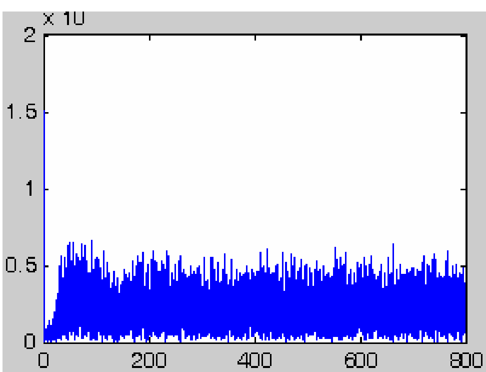

Fig. 1EMG signal passed through the filter

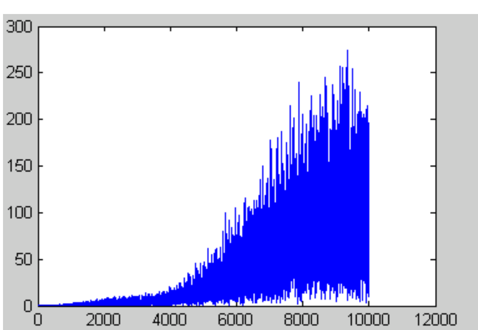

Fig. 2 Broadband Noise passed through the filter

In addition to the classification of a signal as either EMG or Noise, a third category of "no signal" is required. When the muscle is inactive and the noise level is low, the "no signal" condition must be indicated. This state can be easily detected by computing the mean absolute value of the recorded signal – a low value indicates no EMG signal and no noise.

3. Testing for Whiteness: -

In designing a test for whiteness we kept in mind the need to implement the algorithm in real time in hardware. The strategy that can be used to test for whiteness is to pass the output signal through a set of narrow bandpass filters placed at random frequencies in the low, mid & high frequency region. A white signal should contain all frequency components. The presence of the respective frequency component in the whitening filter output signal can be detected either by measuring the peak-to-peak value or the energy of the signal at the outputs of the narrow bandpass filters.

The peak-to-peak value of the band pass output signal taken over a short range can be used as a good estimate of the signal strength at that frequency, if the bandwidth of the bandpass filter is small. The bandwidth that has been used is 10Hz, & hence the peak-to-peak value has been used as a measure of signal strength, where the maxima & minima are found from a small sample of the output signal, large enough to accommodate one complete cycle at the lowest frequency. The peak-to-peak value method has the important advantage of being computationally efficient.

4. Design of Bandpass Filters

A digital filter based on the analog Tscebyscheff filter was obtained by using the Bilinear Transform. There are two points worth mentioning with regard to this filter. Firstly, note that, the filter designed using the above method will not have a linear phase response, or in other words, it will not result in a constant group delay for all frequencies. However, this is not a concern since the output of the whitening filter is a stochastic signal. Secondly, the Bilinear Transform is inherently non-linear in the conversion from analog frequency to the digital frequency. The conversion is given by the relation –

$$\omega = 2 \cdot \tan^{-1}\left(\frac{\Omega \cdot T}{2}\right)$$

This non-linearity in the transformation from the analog to digital domain has been taken care of in the program by pre-warping.

5. Method Summary: -

The AR coefficients may differ for each muscle and therefore the AR coefficients must be determined initially for each muscle. The whitening filter is designed using the muscle specific AR coefficients. The AR coefficients need to be determined only once for any particular muscle. The following figure explains the process of determining the AR coefficients and obtaining the whitening filter.

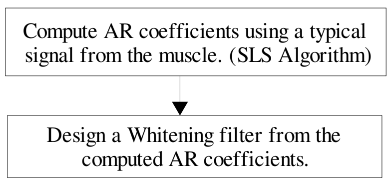

Fig. 3 Design of Whitening Filter for a Muscle

As stated previously, three kinds of signal possibilities are considered – EMG, Noise and No Signal. Shown below is the flowchart of the method to test a given signal.

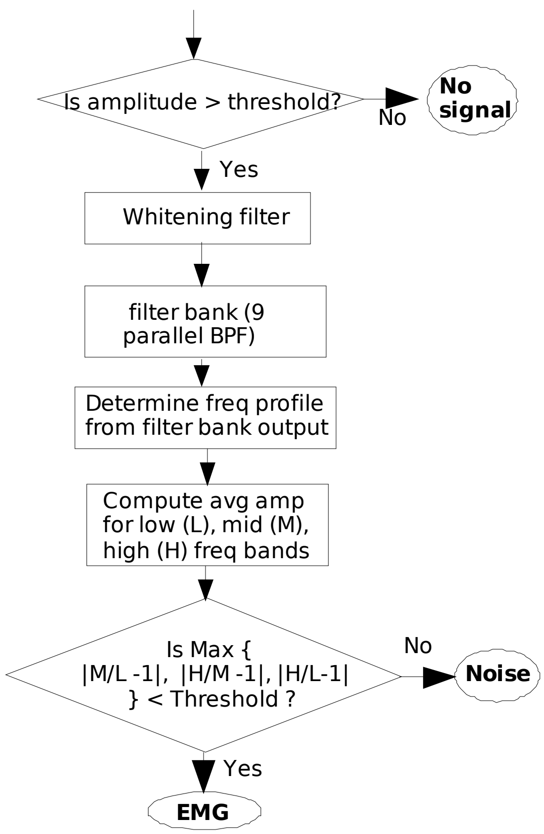

Fig. 4 Method to test an unknown signal

6. Test Results: -

Shown below are the results obtained when the above method was applied to real recorded pure EMG, real recorded EMG corrupted with powerline noise and simulated white noise: -

a) Recorded Pure EMG and wideband noise: -

The EMG amplifier used for recording is a direct coupled instrumentation amplifier with input impedance greater than 1 Gigaohm; passband is 15Hz to 750 Hz, sampling rate is 1600 Hz, stored using 8 bit values.

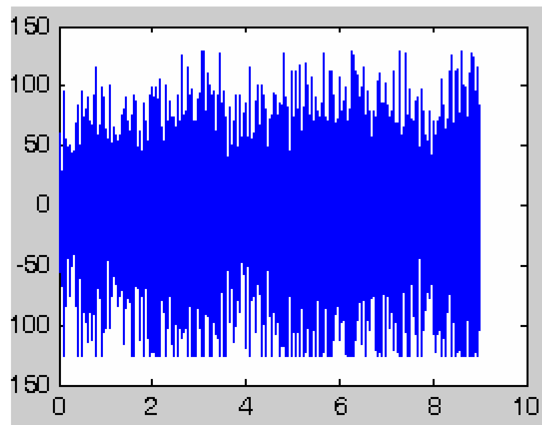

Fig 5 Plot of the recorded pure EMG

The following table lists the peak-to-peak value of the sinusoids at the output of the bandpass filters, when EMG and wideband noise is applied as input to the whitening filter. Three narrow bandpass filters have been placed each in the low, mid and high frequency region. The center frequencies of these bandpass filters have been selected arbitrarily subject to the only criterion that the higher frequencies are not multiples (harmonics) of the lower ones. Here, the frequencies have been selected as arbitrary prime numbers. As expected theoretically, the output for EMG is uniform at all frequencies, i.e. white, however, the output for wideband noise is low at frequencies in the low frequency range.

Freq	**Peak-to-peak value**		
	EMG	**White Noise**	
47	14.34	9.11	Low Freq Range
109	16.82	6.45	
199	10.89	8.07	
307	12.69	14.22	Mid Freq Range
373	12.07	12.49	
457	8.85	31.38	
523	11.84	63.60	High Freq Range
631	12.98	82.53	
719	14.50	105.61	

Table 1 Filter outputs for EMG and wideband noise

The mean values of the peak-to-peak amplitude and their ratios are as follows –

	Vlow=L	**Vmid=M**	**Vhigh=H**
EMG	14.01	11.20	13.10
Noise	7.87	19.36	83.91

M / L	H / M	H / L	Max{|x/y–1|}
0.80	1.17	0.93	0.20
2.46	4.33	10.66	9.66

Table 2 Ratios for EMG and wideband noise

Thus setting the threshold for maximum deviation from 1 as 0.25 would be a good test to distinguish between EMG and noise.

b) EMG corrupted with Powerline Noise

The sampling frequency for the following recording was 20 kHz.

Freq	Peak-to-peak value	Average
470	0.694	0.278 (Low freq)
1090	0.119	
1990	0.023	
3070	0.037	0.021 (Mid freq)
3730	0.016	
4570	0.009	
5230	0.015	0.025 (High freq)
6310	0.026	
7190	0.035	

Table 3 Filter results for EMG corrupted with 50Hz noise

M / L	H / M	H / L	Max{|x/y–1|}
0.075	1.19	0.089	12.33

Table 4 Ratios for EMG corrupted with 50Hz noise

As expected, the ratio is far from unity.

7. Complexity Analysis

Let k: = Order of AR filter
n: = Number of sample points.

In order to determine the coefficients using the SLS algorithm, approximately $(k^3+4k^2+3k)\cdot n$ multiplications and an equal number of additions are required. However, note that coefficients need to be determined only once initially.

In order to pass the signal through the whitening filter and 9 bandpass filters, approximately $81\cdot n+k\cdot n$ multiplications and an equal number of additions are required.

For a typical EMG recording for a duration of 10secs at a sampling frequency of 1600Hz, the number of multiplications and additions is 13,74,600. A typical PIC18F series microcontroller, which requires one instruction cycle per addition and one per multiplication, operating at 5MHz would require barely 0.55 seconds to run the above algorithm. If a DSProcessor is used, the time required would reduce by several orders of magnitude.

8. Conclusion

We have proposed a method to detect the presence of noise in the EMG signal during online recording – i.e. at the site of recording. The methods were implemented with the help of programs written in MATLAB. However, the final objective of implementation using a micro controller or a DSProcessor has been kept in mind and hence wherever possible, computational complexity is avoided without affecting accuracy. The methods were tested using real stored pure EMG data from various muscles, real EMG corrupted with powerline noise, as well as simulated wideband noise, and were found to be working satisfactorily.

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