CLEANEMG: QUANTIFYING POWER LINE INTERFERENCE IN SURFACE EMG SIGNALS

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ABSTRACT

A method for quantifying 50/60Hz power line interference in surface electromyography signals is proposed as part of an ongoing research project, CleanEMG, that aims to provide open source, user friendly methods to assess the quality of surface electromyographic signals. The quantification method is based on interpolating the signal spectrum about its 50/60Hz components to estimate the signal, and then the power line interference. Once these constituents are differentiated, a signal-to-noise ratio may be estimated. A simulation was used to determine when noise due to error in the estimation process surpasses noise from the power line interference. This can be interpreted as the threshold point beyond which removing power line interference via the interpolation method would result in adding noise to the signal. Results indicate a signal-to-60Hz-noise threshold of about 9dB.

INTRODUCTION

Power line interference is a form of structured noise (50Hz or 60Hz and potentially their harmonics). Huhta and Webster [1] site four main sources for this type of noise in biosignal measurements (while their emphasis was on electrocardiography (ECG), the sources apply equally to electromyography): 1) magnetic induction to the electrode leads, 2) displacement current in the electrode leads, 3) displacement current in the body of the person under test and 4) common mode voltage from capacitive coupling between the body and power line sources. The common mode voltage can be suppressed to some degree, but often appears in a recording because of a finite common-mode rejection ratio in the bioamplifier and common mode impedance imbalances.

Mewett et al. [2] proposed a method of reducing power line interference in surface electromyography signals (sEMG) through spectral interpolation. The power line interference is assumed to be a form of additive noise to the sEMG. Digitized sEMG signals are transformed to the frequency domain via the discrete Fourier transform. The sEMG spectral components at the power line frequency (50/60Hz) are estimated by linear interpolation using the adjacent spectral components. Both amplitude and phase are interpolated. The resultant estimated sEMG spectrum is then transformed back to produce an estimate of the time domain sEMG void of power line interference.

The spectral interpolation method theoretically removes only the spectral components at the power line frequency that are associated with power line interference; this is its advantage over more traditional notch filtering methods which remove all of the spectral components at the power line frequency, including those supposed to be included in the sEMG. Care should be taken however, to ensure that noise introduced as a result of estimation error through interpolation does not degrade the signal beyond what the power line interference does.

In this work, the spectral interpolation method is adopted to quantify power line interference. The power line interference can be estimated by subtracting the sEMG estimated through interpolation from the measured sEMG. The power in the estimated interference and signal can then easily be computed to determine an estimated signal-to-noise ratio (SNR). If a relationship can be established between this estimated SNR and the relative power between noise due to estimation error and noise due to power line interference, then a threshold can be identified for reasonable applicability of the interpolation method.

The sEMG from a moderate to high contraction appears like filtered white Gaussian noise. Unlike other biological signals that have easily discernable characteristics (e.g. ECG), it is difficult to indentify noise in the sEMG. This is especially true for clinicians who may not be instrumentation or signal experts. A method that can automatically quantify power line interference and pursue a reasonable course of action (ie. suggest an alteration in instrumentation settings or effectively eliminate the interference), is therefore prudent.

METHOD

A simulation was used to apply the interpolation method for quantifying power line interference in sEMG to determine the relative power in its estimation error, and for identifying a threshold SNR which could be used to decide when it is useful to apply the method.

Simulating clean and corrupted sEMG

An sEMG simulating tool previously described by MacIsaac et al [3] was used to generate a clean sEMG denoted as $s(t)$. The tool is based on a finite-length model of muscle, originally proposed by Gonzalez-Cueto and Parker [4]. A signal 1 sec in duration (f_s=1000Hz yielding N=1000 samples), made up from 50 motor units with 50-100 fibres/unit firing at (8±0.25)pps was generated. Conduction velocities varied across fibres according to (4±0.25)m/s.

The sEMG was corrupted by adding to it a sinusoid of the form:

$$N_{60Hz}(t) = A \cdot \cos(2pif_0t + \varphi) \qquad (1)$$

where A=1mV is the amplitude defining the power in the interference, f_0=60Hz, is the power line interference frequency and φ is the phase of the interference. (Since, $dt = 1/f_s$, t=(0, 1, 2…1000)ms yielding N=1000 samples).

Given these signals, average power was calculated for each according to the square of its root-mean-square voltage:

$$P_x = \left[\sqrt{\tfrac{1}{N} \cdot \sum_{n=1}^{N} x_n^2}\right]^2 \qquad (2)$$

Estimating sEMG and power line interference using spectral interpolation

An estimate of $s(t)$ given the corrupt signal,

$$s'(t) = s(t) + N_{60Hz}(t) \qquad (3)$$

was obtained by linearly interpolating the corrupted signal's spectrum about the power line interference component. The spectrum was obtained using the standard fast Fourier Transform (FFT) algorithm for the discrete Fourier transform (DFT) with N=1000 samples ($df = {}^{1}/_{T}$=1Hz). An interpolation region F was defined to 1) include the range of frequencies which spanned the rising edge of the amplitude of the spectrum, but 2) exclude the region for which values would be estimated (ie. the range of frequencies spanning the interference) according to:

$$F = \pm[f_L \dots f_{LL}, f_{HH} \dots f_H] \qquad (4)$$

where f_L = 0Hz was the lowest frequency in the rising edge, f_H=90Hz was the highest frequency, and $f_{LL} \cdots f_{HH}$=[58...62]Hz was the excluded estimation range. This range was chosen in accordance to Bai et al [5], who used that range for an ECG power line interference reduction system. The interpolation region included both positive and negative frequencies in the spectrum, though the interpolation process for each was conducted separately.

A best line of fit (in a least square sense) was determined for spectral values within the interpolation region and the slope and intercept for this line were used to estimate spectral components for frequencies within the estimation range. Both amplitude and phase of the spectrum were interpolated.

The estimates were substituted into the spectrum in the estimation range to produce a spectral estimate of the clean sEMG. The discrete inverse Fourier transform was used to generate an estimate of the clean sEMG in the time domain, $\hat{s}(t)$. By subtracting this from the corrupt signal $s'(t)$, an estimate of the noise $\hat{N}_{60Hz}(t)$, was also determined. Given these signals, average power was calculated for each according to the square of its root-mean-square voltage given in (3).

Establishing the threshold signal-to-noise Ratio

Estimating sEMG through spectral interpolation introduces noise into the signal in the form of estimation error, $N_E(t)$. When the power in that noise source is higher than the power in the noise caused by power line interference, it does more harm than good to apply interpolation to remove the interference. It is therefore useful to determine threshold conditions for this to occur.

To determine these conditions, a series of corrupted sEMG (T=1sec) with increasing SNR_{60Hz} were simulated where:

$$SNR_{60Hz} = \frac{P_S}{P_{N60Hz}}. \quad (5)$$

In (4) P_S is the power in the clean sEMG signal and P_{N60Hz} is the actual power in the power line interference. Spectral interpolation was performed on each of the signals to produce estimates of both clean sEMG and power line interference. With these estimates, an estimated SNR_{60Hz} could be determined according to:

$$S\hat{N}R_{60\text{Hz}} = \frac{P_{\hat{S}}}{P_{\hat{N}_{60Hz}}} \quad (6)$$

where $P_{\hat{S}}$ is the power in the estimated clean signal and $P_{\hat{N}_{60Hz}}$ is the power in the estimated 60Hz noise. For each signal, noise due to estimation error was also calculated by subtracting the estimated sEMG from the clean sEMG:

$$N_E(t) = s(t) - \hat{s}(t) \quad (7)$$

and calculating the power according to (3). A ratio between the power in the 60 Hz noise and power in the estimation error could then be calculated. This ratio was plotted against estimated SNR_{60Hz} to determine for which value the power ratio indicated equal powers from noise sources. This value was identified as the threshold SNR, beyond which, interpolation to remove 60Hz noise would do more harm than good. To accommodate for signal variation, the entire process was conducted on 50 signals and the results were averaged.

RESULTS

Figure 1 exemplifies the spectral interpolation process. A segment of the power spectrum of an estimated sEMG is superimposed on a plot of the clean sEMG along with a plot of the corrupted sEMG. The actual signal-to-60Hz-noise ratio for this example was SNR_{60Hz}=1. The estimated SNR, $S\hat{N}R_{60\text{Hz}}$=1.01, and P_{N_E}<0.01 mV^2.

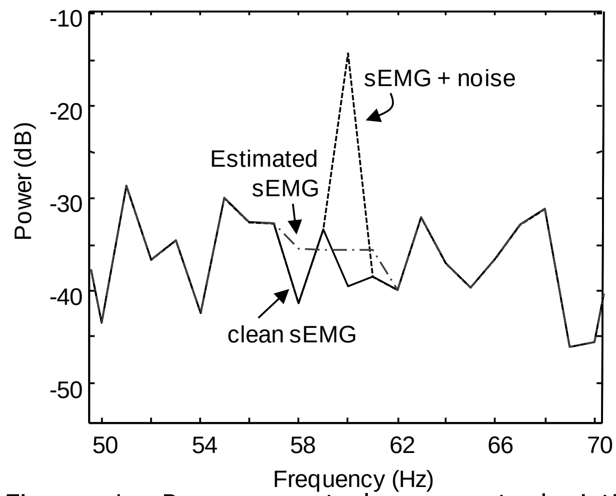

Figure 1: Power spectral segment depicting estimated sEMG superimposed on clean sEMG and corrupt sEMG.

Table 1 lists actual signal and noise powers against estimated signal and noise powers for corrupted signal SNRs (SNR_{60Hz}) ranging from 4 to 20 in steps of 4:

Table 1: Power (in mV^2) in sEMG and noise components (actual and estimated shown), and Estimation Error.

SNR_{60Hz}	P_S	$P_{\hat{S}}$	P_{N60Hz}	$P_{\hat{N}60Hz}$	P_{N_E}
4	2.00	1.96	0.50	0.47	0.18
8	4.00	3.92	0.50	0.57	0.37
12	6.00	5.88	0.50	0.69	0.56
16	8.00	7.85	0.50	0.82	0.74
20	10.00	9.81	0.50	0.96	0.93

All of the values depicted have been averaged across 50 signals. Power in the noise due to estimation error is also listed in the table indicating a upward trend with increasing SNR. The range of SNRs shown focuses on the SNR at which P_{N_E} surpasses P_{N60Hz}. For SNRs below the range shown, P_{N_E} was always less than P_{N60Hz}.

Figure 2 plots the ratio of powers between the two sources of noise (P_{N60Hz} and P_{N_E}) against estimated SNR_{60Hz} (in dB).

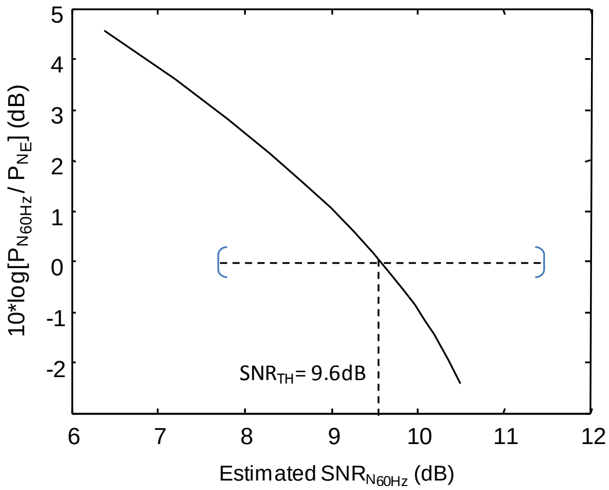

Figure 2: Ratio of Power in noise sources vs estimated signal-to-60Hz-Noise ratio averaged across 50 signals. Standard deviation is shown for threshold point.

The result shown is an average across 50 signals. Also shown on this plot is the estimated SNR_{60Hz} for which the source powers are equal ($10log(P_{N_{60Hz}}/P_{N_E}) = 0$). This represents the threshold condition. Standard deviation across 50 signals for this value is indicated. The estimated SNR_{60Hz} value was used instead of the actual SNR_{60Hz} value, because actual SNR_{60Hz} is not available in the practical scenario. The threshold SNR is about (9.5 ± 1.9)dB.

DISCUSSION

The spectral interpolation process works well to quantify (and reduce) power line interference for SNRs lower than 4dB. The example in figure 1 demonstrates its capacity for SNR values around 1, for the interpolation and estimation ranges specified in this example. Table 2 indicates a degrading performance with increasing signal power and therefore, SNR. Figure 3 depicts the consequences of the degradation. A threshold is clearly visible, though the value for the threshold varied considerably (1 standard deviation = 1.96dB). The variability was not surprising, since the interpolation process was dependent on a rough estimate of the spectrum, a relatively arbitrary cutoff for the interpolation range, and a value asserting strategy that has little meaning with regards to spectral phase. Perhaps by mitigating some or all of these factors, the SNR threshold may be ascertained more accurately. Other considerations still to be handled are influence of frequency resolution (and therefore signal length) and interference jitter (about 60Hz), especially when minimum estimation regions are specified.

CONCLUSIONS

Spectral interpolation for quantifying power line interference in sEMG has been demonstrated. Quantification can be useful to ensure that the interpolation process does not increase noise in the signal. This may have limited use in sEMG since improvements are expected for SNRs up to about 9dB; however, in signals with higher concentrations of 60 Hz content (such as ECG signals), quantification may be even more prudent. Quantification may also be useful in confirming properly set instrumentation, even in sEMG studies. This work represents a preliminary step in the directions set for the cleanEMG project.

ACKNOWLEDGEMENTS

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