A Simulation Study of Unwhitened Versus Whitened EMG Amplitude Estimation

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Abstract — Amplitude estimates of simulated surface electromyograms (EMGs) were studied using both unwhitened and whitened EMG amplitude estimators. Constant-effort non-fatiguing EMGs were simulated as the superposition of simple synthetic motor unit action potential trains (MUAPTs). Each MUAPT was formed from random firings of randomly shaped motor unit action potentials. Two aspects of unwhitened vs. whitened amplitude estimators were studied: 1) the relationship between the mean value of the EMG amplitude estimate vs. the level of contraction and 2) the signal-to-noise-ratio (SNR) performance of the EMG amplitude estimate. It was found that the relationships between estimated EMG amplitude vs. MUAPT firing rate and the number of MUAPTs were not altered by whitening. However, the performance of whitened amplitude estimators was markedly better. These results suggest that whitening can provide a higher fidelity EMG amplitude estimate without distorting the relationship between EMG and the mechanical output of the muscle.

INTRODUCTION

Historically, [1] are credited with the first EMG amplitude estimator. They implemented a full-wave rectifier followed by a simple resistor-capacitor low pass filter. In recent years, investigators have shown experimentally and analytically that temporal whitening of the EMG signal improves the amplitude estimate by 35–100%.

Several authors have developed models of the surface EMG which draw upon underlying physiology. In general, these models begin by describing the observed electrical activity due to a single motor unit (MU) — the motor unit action potential (MUAP). Repeated stimulation of an MU produces a series of these MUAPs to form an MUAPT. Typically, many MUs are active during a normal contraction. The surface electrode observes the composite activity of those MUs within its recording field. In order to provide some conceptual simplification to this physiologic model, [2] defined a generalized firing rate as the mean value of the firing rates of the MUAPTs detected during a contraction.

In the study described herein, a simple version of the above model was implemented. The generalized firing rate and number of MUs in each simulation trial were selected as different fixed values. Thus, the model surface EMG was due to a simulated constant-effort non-fatiguing contraction. Amplitude estimation was then performed on the simulated EMG from each trial with both unwhitened and whitened techniques. Two specific comparisons were made between the two techniques. First, the relationship between the mean value of the estimate from each technique was related to the underlying generalized firing rate and number of MUs. Second, the SNR performance of the estimate was investigated.

METHODS

The overall simulation technique was to create MUAPTs by randomized firings of randomly shaped MUAPs. The contributions from several MUAPTs were superimposed to create the surface EMG. Simulated monopolar MUAPs were assigned a voltage according to: $\mathrm{AP}(t) = \dfrac{\text{Scale}}{\sqrt{x^2(t) + y^2}}$. The distance y was fixed as one distance unit. "Scale" was randomly assigned from a doubly truncated normal distribution with a mean value of 1.0, a variance of 0.0625, and truncated over the range 0.1–10.0. The distance x was incremented from a large negative distance (−250 distance units) to a large positive distance (250 distance units) by one distance unit for each increment in unit time. In this manner, the excitation site changed location, simulating MUAP propagation. The time at which x equaled zero was considered the firing time of the MU. One time unit was equal to 1/2048 seconds.

A bipolar MUAP was formed by adding one randomly scaled monopolar MUAP to a second, time-delayed, negated, randomly scaled monopolar MUAP. Geometrically, this addition simulated two bipolar leads of an electrode pair oriented along the direction of MUAP propagation. The time delay was eight time units (3.9ms). An MUAPT was created by assigning random successive inter-pulse intervals (IPIs) to the firing times of a MUAP. IPIs were randomly assigned from a doubly truncated normal distribution with a mean value equal to the mean firing interval, a variance equal to one quarter of the square root of the mean firing interval, and truncated over the range 50–400 time units (24–195ms). This distribution was selected to produce IPIs which were grossly similar to those measured by [3]. Any particular MUAP maintained a fixed shape throughout a simulation trial. Distinct MUAPs had distinct shapes.

The simulated surface EMG was created as the zero mean sum of several MUAPTs. An initial startup time (195ms) was discarded, and the ensuing five simulated seconds was analyzed. The number of MUs and the mean firing rate (inverse of the mean firing interval) were selectable for each simulation trial.

Unwhitened and whitened EMG amplitude estimates were formed from the data of each simulation trial. The unwhitened estimator was a 245ms moving-average root-mean-square (MARMS) filter. The whitened estimator was a fourth-order moving-average whitening filter followed by the 245ms MARMS filter. To construct the whitening filter, the waveform simulation data from all simulation trials (32) were ensemble-summed, forming one composite five-second data trial. The power spectrum of the composite trial was estimated with a fourth-order autoregressive model. The coefficients of the fourth-order autoregressive model specified the fourth-order moving-average whitening filter. This filter was used for all 32 trials. For each trial (unwhitened and

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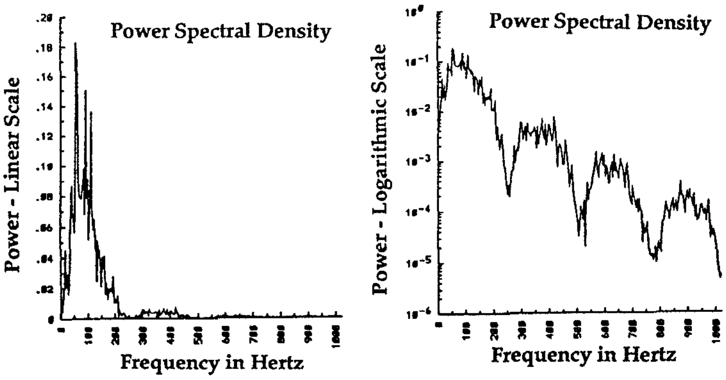

Fig. 1: Power Spectrum of Simulated EMG Waveform
The simulation model utilized 100 MUs and a mean firing rate of 15 pulses/second. Plot at left is the Discrete Fourier Transform (DFT) PSD, plotted to a linear scale. Plot at right is the DFT PSD, plotted to a logarithmic scale.

whitened) an SNR was computed as the square root of the ratio of the squared amplitude estimate sample mean divided by the amplitude estimate sample variance. See [4], [5] for additional details of the methods.

RESULTS

Initially, the number of MUs was fixed at 100 and the firing rate was ranged from 5–20 pulses/sec in increments of 1 pulse/sec. Then, the firing rate was fixed at 15 pulses/sec and the number of MUs ranged from 50–200 in increments of 10. Thus, a total of 32 simulations were performed.

Fig. 1 shows the power spectral density (PSD) of a sample simulated EMG waveform. Amplitude estimation with the unwhitened estimator yielded an SNR performance of 13.9±1.6 (mean ± std. dev. of the 32 trials). Amplitude estimation with the whitened estimator yielded an SNR performance of 24.7±3.2, a 78% improvement over the unwhitened estimator. Finally, in Fig. 2 the sample means of the EMG amplitude estimates from each trial are plotted vs. the mean firing rate. Similar results are found when plotting vs. the number of simulated MUs.

DISCUSSION

Fig. 1 shows that the simulated EMG waveform PSD looks similar to that of experimental data. The linear PSD plot shows a characteristic shape with maximum powers in the 50–150 Hz range, and greatly diminished power above 200 Hz. The logarithmic PSD plot shows three dips in the spectrum of the data. These dips, or cancellation frequencies, are due to the differential electrode filter effect, and occur at multiples of the muscle fiber conduction velocity (v) divided by the electrode separation distance (d) which are related as: $v \cdot \text{delay} = d$, where "delay" is the time for an MUAP to propagate from one electrode to the other. This time delay was 3.9ms, thus the cancellation frequencies occur at 256, 512 and 768 Hz. The SNR results, both for the unwhitened and whitened data, are similar to that of experimental data. In addition, for changes in either average firing rate or number of simulated MUs, the whitened estimate was essentially a scaled version of the unwhitened estimate — except that the whitened estimate exhibited superior SNR.

SUMMARY

A simple model of constant-effort non-fatiguing surface EMG, based on the superposition of synthetic MUAPTs, was described. The generalized firing rate and number of MUs used in each simulation trial were programmable. Amplitude estimation was then performed on the EMG using both unwhitened and whitened techniques. The study found that the relationships between estimated EMG amplitude vs. MUAPT firing rate and number of MUAPTs were not altered by whitening. However, the SNR of whitened amplitude estimators was markedly better. These results suggest that whitening can provide a higher fidelity EMG amplitude estimate without altering the relationship between EMG and the mechanical output of the muscle.

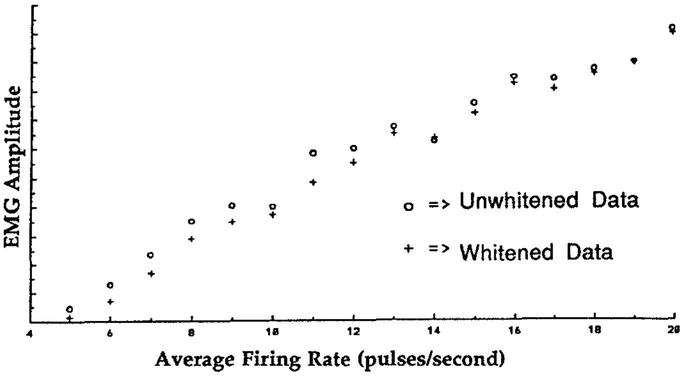

Fig. 2: EMG Amplitude vs. Firing Rate
Sample mean of the EMG amplitude vs. the average firing rate for unwhitened and whitened estimators. Each estimator is independently normalized to its maximum value and graphed to a linear scale.

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