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# Simplified Implementation of Optimized Whitening of the Electromyogram Signal

He Wang[1], Kiriaki J. Rajotte[1], Haopeng Wang[1], Chenyun Dai[2], Ziling Zhu[1], Moinuddin Bhuiyan[1], Edward A. Clancy[1]
[1] Worcester Polytechnic Institute (WPI), USA; [2]Fudan University, China

**Introduction:** The surface electromyogram (EMG) signal is well modeled as an amplitude modulated, correlated random process. The amplitude modulation, defined as the time-varying standard deviation (EMGσ) of the signal, is used in various applications as a measure of muscle effort, e.g., EMG-force models, prosthesis control, clinical biomechanics and ergonomics assessment. EMGσ can be estimated by rectifying the EMG and then lowpass filtering (cutoff ~1 Hz). However, it has long been known that the correlated nature of EMG reduces the statistical efficiency of the EMGσ estimate, producing a large variance.

To combat this problem, a whitening filter can be used prior to the rectifier. Whitening removes signal correlation—while preserving signal standard deviation—producing a substantially improved EMGσ. The advantages of whitening filters have been known since at least 1974 [3]—yet, few researchers use them. A key limitation to widespread use is that most whiteners are "calibrated" to each subject, making them cumbersome to implement.

Since EMG whitening filters have low gain at low frequencies and higher gain at high frequencies, Potvin [4] implemented simple whitening via a fixed, *low-order*, FIR, *highpass* filter that was *not* calibrated to individual subjects. This approach was not compared to the established technique of subject-specific whitening filters.

Our work reported herein describes development of a simplified whitening technique that relies only on EMG magnitude normalization (a measure that is already common). We compare this technique to state-of the art subject-specific whitening.

**Experimental Methods:** Pre-existing data from 64 subjects [5] were used and did not require human studies supervision per the WPI IRB. Four electrodes over the biceps and four over the triceps muscles were acquired during three trials of 30-s duration, constant-posture, force-varying elbow contractions in which subjects followed a target displaying a 1 Hz bandlimited, uniform and random process, spanning 50% maximum voluntary contraction (MVC) flexion to 50% MVC extension. Using our existing subject-specific technique to form whitening filters for each electrode (calibrated from additional 5-s rest recordings and constant-effort 50% MVC trials, and limited to 600 Hz in frequency [6,7]), we related EMGσ to force. This EMGσ-force model used each of the eight EMGσ values as inputs, a 15th-order dynamic FIR model per EMGσ, additionally included the squared value of each EMGσ at the 15 time lags (to model the EMG-force non-linearity), and was trained from two trials using least squares. The average ± std. dev. test error on the distinct third trials was 4.84±1.98% flexion MVC ($\%\text{MVC}_F$). This error served as our "baseline" performance.

**Analysis Methods and Results:** Our whitening filters (Fig. 1) are comprised of a fixed whitening filter followed by an adaptive noise canceller (with variance preservation). The first stage is a fixed linear filter whose magnitude response is the inverse of the square root of the power spectral density (PSD) of the noise-free EMG signal (estimated by subtracting the 0% MVC PSD from the 50% MVC PSD). This filter has low gain at low frequencies and higher gain at high frequencies—the opposite of the spectral content of EMG. The second stage cancels high frequency noise, above the dominant frequency of EMG. This filter is a time-varying lowpass filter, with a cut-off frequency that is lower at lower effort levels. The time adaptation is set via a first-pass unwhitened EMGσ estimate. The gain of this stage preserves the overall power of the noise-free signal, so that the full whitening process does not alter EMGσ.

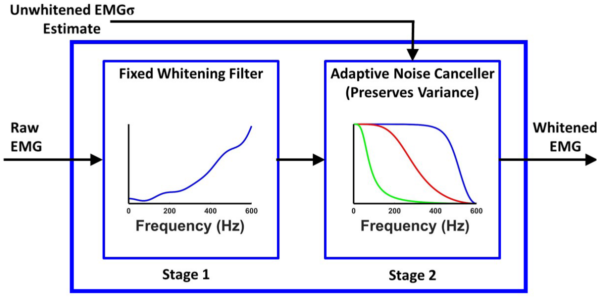

Fig. 1. Two-stage adaptive whitening filter [6].

We contrasted subject-specific whitening filter calibration to "universal" calibration. Each EMG was gain normalized, to account for gain variations between channels. Thereafter, the 0% MVC PSDs and (separately) the 50% MVC PSDs were ensemble-averaged across the 512 calibration recordings (64 subjects x 8 electrodes/subject). The one, ensemble-averaged 0% MVC and the one, ensemble-averaged 50% MVC were then used to form a single "universal" two-stage whitening filter. This filter was then similarly evaluated on the EMG-force data, producing an average ± std. dev. test error of 4.80±2.03 $\%\text{MVC}_F$—the same as that of subject-specific whiteners.

**Conclusions:** Our work, combined that of Potvin [4], suggest that the PSD of EMG is sufficiently consistent subject-to-subject that subject-specific calibration of PSDs for EMG whitening may not be necessary (for noise cancellation). Only a gain normalization may be needed per channel. Note that PSD shapes are known to vary with inter-electrode distance [1] and might vary muscle-to-muscle. Also, this set of dynamic contractions may not be particularly sensitive to the magnitude of the noise power, since few of the active-trial contractions were near 0% MVC. (Noise is most impactful at low contraction levels.)

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