Abstract— Previous works have shown that whitening improves the processed electromyogram (EMG) signal for use in end applications such as EMG to torque modelling. Traditional whitening methods fit each subject from calibration contractions, which is a hindrance to their widespread use. To eliminate this cumbersome calibration, a universal whitening filter was developed using the whitening filters from a pre-existing data set (64 subjects, 8 electrodes/subject). Since the shape of each subject-specific whitening filter was observed to be relatively consistent across subjects, the universal whitening filter was formed as their ensemble average. The processed EMG was then used to model surface EMG to torque about the elbow. Traditional and universal whitening provided the same EMG-torque benefit, each improving statistically over unwhitened processing by ~14% during dynamic contractions. We further studied the use of root difference of squares (RDS) post-processing to attenuate additive measurement noise in EMG channels. With and without whitening, RDS processing (vs. no RDS processing) better attenuated additive noise, reducing it from 2–4% (on average) of the processed EMG from a 50% contraction down to < 1%. The combined use of universal whitening filters and RDS processing should be a particular benefit in real-time applications such as prosthetic control.

I. INTRODUCTION

Since at least 1952 [1], estimates of the standard deviation of the surface electromyogram (EMG) signal (EMGσ) have served as a global measure of motor unit activity/muscular activation [2]. EMGσ estimates have been used to estimate torque [3-8] and mechanical impedance [9-14] about a joint, in motor control research [15], and in applications such as prosthetic control [16-18], ergonomic assessment [19, 20] and clinical biomechanics [21, 22]. Advanced single-channel EMGσ estimates, implemented in software, are formed from the cascade of: a highpass filter at 10–20 Hz (to remove DC offsets and attenuate motion artifacts), a whitening filter (to temporally uncorrelated the samples), a detector (square or absolute value), an averager/lowpass filter (f_s typically a few Hz or less), and a relinearizer [23].

Alas, the whitening stage is commonly not utilized, perhaps because it is not mandatory (it reduces the variability of EMGσ, but does not alter the average value [24-26]) and because it can be complex to implement. But, the reduction in variation is considerable—and depending on the duration of the averager [27], whitening has increased the signal-to-noise ratio (SNR) of constant effort contractions by 32–64% [25, 28]. In turn, EMGσ applications benefit [3, 9, 29, 30].

As for the complexity of whitening, Kaiser and Peterson [31] adaptively varied the bandwidth of their analog whitening filter in an ad hoc manner to admit a larger frequency range during higher contraction levels, wherein the EMG signal power remained above that of the noise over a wider frequency span. Clancy and Farry [26] formalized this signal vs. noise trade-off as a function of frequency by cascading a fixed whitening filter with an adaptive Weiner filter (optimal linear filter when signal and noise are added). But their filters were calibrated to each subject using active and rest contractions; a requirement that is taxing to many.

Potvin and Brown [32] demonstrated simplified whitening by using a first-order Butterworth highpass filter with cut-off frequency of 410 Hz for all subjects, and limited whitening out to a range of 500 Hz. The low order of the filter causes it to act more like a shaping filter than an ideal highpass filter. This filter shape, and its performance, was similar to that of a whitening filter. Their filter showed a simplified way to process the data in a manner similar to whitening by attenuating some of the lower frequency components of the signal, but did not adaptively attenuate noise as a function of effort level, as did the methods of [31] and [26].

The work completed by Potvin and Brown [32] led to an interesting conclusion about the adaptability of the whitening filter; their work showed no significant performance differences when a single filter was applied to all subjects in their data set. With this in mind, we proposed the development of a universal whitening filter, including adaptive noise cancellation. Traditional whitening filters are developed specifically for each subject and can become complex especially when developing and implementing in a real-time operating system. A universal whitening filter will ease the implementation of whitening and may increase the practice of whitening in EMG processing.

II. METHODS

A. Experimental Data

The data analyzed in this work were measured from 64 subjects across four prior experiments [3], [26], [33], [34]. The WPI Institutional Review Board approved the re-use of these data for this analysis. The data were collected from eight custom-built, active bipolar electrodes (4 or 8 mm diameter, separated 10 mm edge-to-edge; passband 15–1800 Hz) with a ninth electrode used as a reference. Four active electrodes
were placed transversely over the biceps and four over the triceps, each halfway between the elbow and the midpoint of the upper arm. Prior to placing the electrodes, the surface of the skin was cleaned with alcohol and electrode gel was applied. A subject was seated and secured with belts in a custom-built straight back chair with their right shoulder oriented at a 90° angle upwards in the coronal plan. Their right wrist was strapped to a load cell such that a 90° angle was formed between their forearm and upper arm and their hand was positioned with their thumb pointed upwards.

Then, maximum voluntary contractions (MVCs) were measured. Constant-force, constant-pose contraction data (two trials, each 5-s duration) were collected at rest (0% MVC), 50% MVC extension and 50% MVC flexion. Lastly, three 30-s duration, dynamic-force, constant-pose trials were collected (1 Hz bandwidth, random uniform target spanning 50% extension to 50% flexion). All EMG channels and the load cell data were sampled at 4096 Hz (16 bits). Three minute rest periods were given between trials to avoid fatigue. Offline, each EMG channel was highpass filtered (15 Hz cut-off, fourth-order Butterworth); IIR notch filtered at 60 Hz and its harmonics (2nd -order); and bandlimited to 600 Hz [35]).

B. Development of the Universal Whitening Filter

Traditionally, whitening filters have been calibrated specific to each subject and have matured from a fixed filter to the cascade of a fixed whitener with an adaptive noise canceller (Fig. 1)—to overcome failures at low EMG effort levels due to noise [26]. Subject-specific implementation of the two-stage whitening filter can be tedious and difficult especially in a real-time operating system.

A traditional fixed whitening filter is custom designed for each subject using the reciprocal of the “true” EMG power spectral density (PSD). The true EMG PSD is estimated by spectral subtraction of the noise PSD (i.e., 0% MVC) from the PSD of an active EMG trial (e.g., 50%). An adaptive noise canceller is also calibrated using both 0% and 50% MVC trials. To evaluate if the whitening filter need be subject-specific, these PSDs were computed for each subject, with a 60th-order FIR two-stage whitening filter formed [26]. For PSD estimation, the Welch method was employed with a Hamming window, 50% overlap and a 2048 point discrete Fourier transform.

Then, a 60th-order FIR two-stage universal whitening filter was derived using the ensemble average of the 512 available subject-specific filters (64 subjects x 8 electrodes/subject). The magnitude response of the universal fixed whitening stage is shown in Fig. 2.

III. RESULTS

To test the performance of the universal whitening filter against traditional adaptive whitening filters, both techniques were used to estimate EMG torques in the dynamic data. Once EMG torques were computed, it was used to model the relationship between surface EMG and torque about the elbow [3-8]. Two dynamic trials were used to form a model and the third trial was used for testing. Models were formed using regression (15th-order quadratic FIR model, Moore-Penrose inverse with a maximum ratio between the largest and smallest singular value of 0.0056 [3]). Root-mean squared (RMS) error between the actual torque measured and the estimated torque, summarized across the 512 trials, is shown in Table 1.

The universal whitening filter exhibited performance, on average, that did not differ statistically from the traditional adaptive whitening filter. The Kolmogorov-Smirnov Test of Normality found the data to be non-parametric, so statistical evaluation was conducted using the Friedman Test. This test found a statistically significant difference between the three methods (p < 0.05). Post-hoc Wilcoxon signed-rank pairwise tests (Bonferroni corrected) found that each whitening filter performed better than the unwhitened data (p < 0.05) but did not differ from each other (p > 0.05). These results suggest that the universal whitening filter can replace traditional adaptive whitening filters without loss of performance in this end application.

<table>
<thead>
<tr>
<th>Test Scenario</th>
<th>Mean ± StandardDeviation of the RMS Error (%MVC)</th>
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<tbody>
<tr>
<td>Unwhitened</td>
<td>5.50 ± 2.5</td>
</tr>
<tr>
<td>Traditional Adaptive Whitening Filter</td>
<td>4.84 ± 1.98</td>
</tr>
<tr>
<td>Universal Whitening Filter</td>
<td>4.80 ± 2.03</td>
</tr>
</tbody>
</table>
IV. SUBTRACTION OF ADDITIVE NOISE

Using several variations of Stage 2 (including its absence) [36], we anecdotally found EMG-force performance to be insensitive to the shape of the adaptive noise cancelling filter in the above application. This observation may be due to the fact that very little of the dynamic force data include low-level EMGσ; EMG measurement noise is primarily an issue at low effort levels. Thus, to further optimize the estimation of EMGσ, mathematical models of EMG in additive noise were used to prove that the optimal subtraction of additive noise when estimating EMGσ is the root difference of squares (RDS) [37]. To further improve the estimation of EMGσ, RDS processing was implemented alongside universal whitening, specifically comparing performance at 0% MVC (low level) to 50% MVC (high level).

A. Methods

To compare EMGσ estimation with vs. without RDS processing, a constant force 50% MVC (high-effort) recording and a rest contraction (lowest possible effort) were used. The EMG data were either unwhitened, traditionally whitened, or universal-filter whitened. These pre-processed EMG data were then rectified and smoothed (mean absolute value, MAV) using a 200 ms moving average window. To account for transients, 200 ms of data were then removed from the beginning and end of each signal. When RDS was implemented, the computation was:

$$\hat{s}_{MAV} = \sqrt{\max\{0, (\sqrt{2} \text{MAV})^2 - q^2\}}$$

(1)

where \(\hat{s}_{MAV}\) is the final EMGσ estimate formed from RDS processing of the MAV and \(q^2\) is the variance of the noise (after optional whitening). This final EMGσ was computed for 50% MVC data and rest data from each subject. RDS processing is expected to have a greater impact on lower effort level contractions than on higher level contractions [38].

B. Results

To understand the impact of RDS processing on the two different effort levels with the universal whitening filter, six different scenarios were considered: all combinations of three whitening methods (unwhitened, traditional subject-specific whitening, universal whitening) and two RDS processing methods (with, without). To compare the impact of each of these scenarios, the time-average value (across the constant-effort trial) of the final EMGσ at 0% MVC was divided by the time-average value of the final EMGσ for the 50% MVC from the same scenario. We chose this ratio since, as expected, RDS processing produced a barely detectable change in EMGσ at 50% MVC, but whitening alters the overall signal gain. Lower ratios denote better performance.

Statistical testing was used to detect significant differences between the six scenarios. The Kolmogorov-Smirnov Test of Normality showed that the data were non-parametric. The non-parametric Kruskal-Wallis test with a significance level of \(p = 0.05\) was used to rank and compare the ratios according to the median to determine if significant differences existed. Post hoc Paired t-tests with Bonferroni correction (to compensate for multiple comparisons) was used. Results of the statistical testing are shown in Fig. 3.

C. Discussion

As theoretically predicted, RDS processing significantly improved noise rejection for the rest contractions; the median value of the ratios with RDS processing were less than the median values of the ratios without RDS processing. The range of ratio values (25th and 75th percentile) also decreased with RDS processing. When RDS processing was used, the different whitening methods had similar performance, although the traditional subject-specific method was statistically better than the universal filter. Additional evaluation during lower-effort force-varying contractions would be appropriate for future work, since most human activity occurs at effort levels well below 50% MVC.

V. DISCUSSION

To develop the universal whitening filter, the ensemble average of 64 subject-specific whitening filters was computed and the coefficients of the 60th order FIR filter stored in a matrix to be accessed whenever the universal whitening filter is implemented. To implement a more efficient filter, the magnitude response of the universal filter can be used to develop a new filter with a lower filter order or different filter type. We have done so using a genetic machine learning algorithm [36], reducing the filter computation to second-order IIR, without a loss in performance. Development of a lower order filter reduces the computation needed to implement whitening and makes whitening simpler to execute in real time systems such as a prosthesis. Future work should evaluate the performance of universal whitening and RDS processing in applied problems (e.g., prosthesis control, clinical biomechanics), either offline (e.g., [39]) or on-line, as performance improvements within an application may vary.

VI. CONCLUSIONS

A universal whitening filter was successfully developed from subject-specific adaptive whitening filters and its performance was comparable to that of the traditional
whitening filter, but with reduced complexity. A simpler, universal whitening method is a computationally efficient method to temporally uncorrelate the samples of measured surface EMG. Additionally, the universal whitening filter was implemented with RDS processing to further optimize the EMG estimate due to additive noise. The advantages of RDS processing are most noticeable at low contraction levels.

REFERENCES