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High-pass filtering to remove electrocardiographic interference from torso EMG recordings

M S Redfern PhD[1], R E Hughes PhD[2], D B Chaffin PhD[3]

[1]Movement Analysis Laboratory, The Eye & Ear Institute of Pittsburgh, The University of Pittsburgh; [2]Safety and Health Assessment and Research Program Washington State Dept. of Labor and Industries; and [3]Center for Ergonomics, The University of Michigan, USA.

Summary

Removal of electrocardiographic (ECG) contamination of electromyographic (EMG) signals from torso muscles is often attempted by high-pass filtering. This study investigated the effects of the cut-off frequency used in this high-pass filtering technique on the resulting EMG signal. Surface EMGs were recorded on five subjects from the rectus abdominis, external oblique, and erector spinae muscles. These signals were then digitally high-pass filtered at cut-off frequencies of 10, 30, and 60 Hz. Integration and power analyses of the filtered EMGs were subsequently performed. It was found that an increase in the cut-off frequency affects the integrated EMG signal by (1) reducing the ECG contamination, (2) decreasing the amplitude, and (3) smoothing the signal. It was concluded that the use of a high-pass filter is effective in reducing ECG interference in integrated EMG recordings, and a cut-off frequency of approximately 30 Hz was optimal.

Relevance

Electromyographic recordings of torso muscles are often used in the development of low-back biomechanical models. Unfortunately, these recordings are usually contaminated by electrocardiographic interference. High-pass filtering methods are sometimes used to diminish the influence of ECG from surface EMGs; however, the effects of these filters on the recorded and processed EMG have not been reported. The findings show that high-pass filtering is effective in reducing ECG contamination and motion artefact from integrated EMGs when the appropriate cut-off frequency is used. Inappropriate cut-off frequencies lead to either incomplete ECG removal or excess filtering of the EMG signal.

Key words: EMG, ECG, surface, filtering, torso, muscles

Introduction

Electromyographic recordings (EMG) are widely used to understand the firing patterns of muscles during exertions. In biomechanics, the EMG signals are usually processed by integration, root mean square or low-pass filtering to obtain a representation of the level of activity in the muscle. Other processing could include power spectral analysis for localized muscle fatigue evaluation. Torso muscle EMGs, however, are often contaminated with electrocardiographic (ECG) signals emitted from the heart, low-frequency motion artefact, and cross-talk. The recorded signal at the electrode site is then a superposition of these contaminating signals and the EMG signal of interest. Some procedures for removing the ECG have been proposed in the literature for specific applications of indwelling electrodes[1-3] and surface electrodes[4]. The use of a high-pass filter on the recorded signal is one common method used in biomechanics research; however, the effects of such a procedure have not been reported. This study examines the effect of the cut-off frequency used in high-pass filters to remove the ECG from contaminated torso EMG on the final processed EMG.

Methods

Bipolar silver–silver chloride surface electrodes

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Correspondence and reprint requests to: Dr M Redfern, The Eye and Ear Institute, Suite 500, 203 Lothrop Street, Pittsburgh, PA 15213, USA

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(HP14445C) with a centre-to-centre interelectrode spacing of 30 mm were placed over the rectus abdominis, external oblique, and erector spinae muscles. The rectus abdominis electrodes were located 20 mm lateral to the mid-line. Electrodes were placed at three levels of the erector spinae muscles: L_1, L_3, and T_9. The electrodes were placed 30 mm lateral to the spinous process at each level. The external oblique electrodes were placed 30 mm superior and anterior to the anterior superior iliac spine. The electrode placement procedure for the external oblique was the same as used by Schultz, et al.[5]. All electrode pairs were positioned longitudinally with respect to the muscle fibres. An electrode pair was also placed on the chest to record pure ECG, with one electrode on the sternum and the other placed laterally at the level of the sixth rib. The ground electrode for all recordings was placed over the acromion process. All signals were preamplified by 100×, low-pass filtered at 10 kHz, and passed through shielded cable to a microcomputer via an A/D converter at a sampling rate of 500 Hz.

Five healthy subjects performed a series of five second trials with 2 min of rest between trials. The subjects were fitted with a harness that could impose a horizontal force in the mid-sagittal plane to the torso, either posteriorly or anteriorly. The pelvis was strapped against a brace for support. The subject was asked to resist this force isometrically, thus remaining in an upright posture. Both posterior and anterior static loads were imposed to the subject by attaching a line from the harness through a pulley to a hanging weight. The line was attached first to the anterior of the harness for the extension trials, then to the posterior for the flexion trials. The exertions chosen for this study were 0, 10, 20, 40, and 100 per cent of maximum voluntary contraction (MVC) in extension and flexion, thus requiring varying levels of resistance from the torso muscles to maintain upright posture. Recordings from the electrodes were made during each of the trials.

Once collected and stored, post-processing of the data by high-pass filtering was performed using digital finite impulse response (FIR) filters with 100 coefficients based on a Hamming window design criteria. Cut-off frequencies of 10, 30, and 60 Hz were used. A common digital integrator with an exponential window[6] was used to calculate the integrated EMG (IEMG) before and after the filtering was performed. A time constant of 125 ms was used on the integrator.

Power content of EMGs were estimated for the filtered and unfiltered signals at individual force levels. These values were found to determine the proportion of power in the EMG signal for each filter level. The power calculations were found by digital integration of the square of the signal, then dividing by the total trial time.

Results

Cut-off frequency effects

The magnitude of EMG data recorded for the different trials increased with increasing force applied. Figure 1 shows a typical recording from all the muscles tested for a 20% MVC extension exertion. The ECG contamination was identified by the ECG recording leads. Note that the ECG contamination varies as a function of

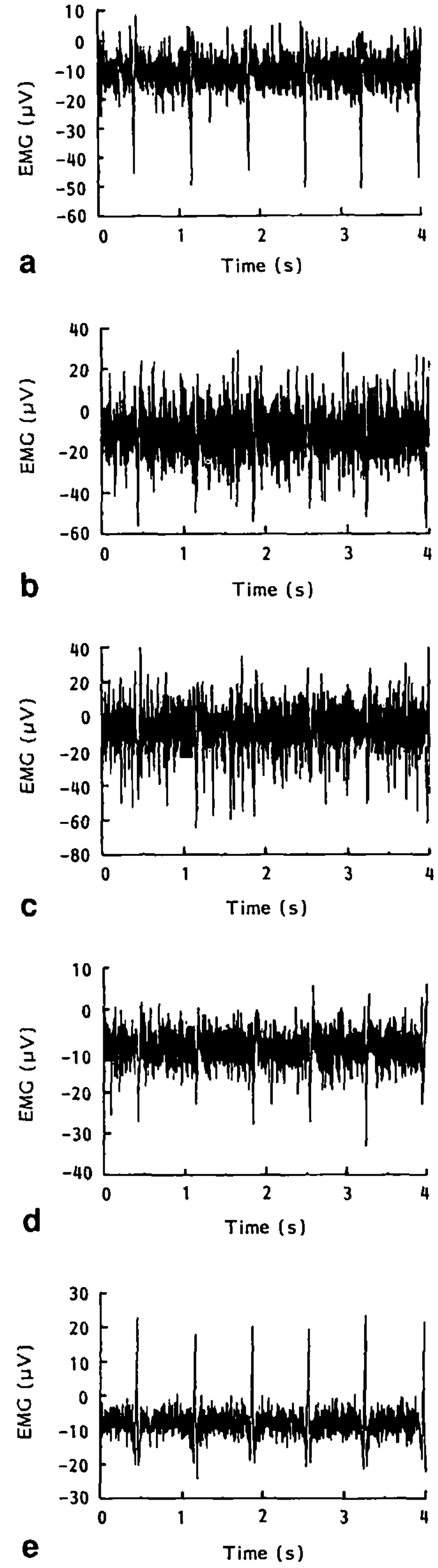

Figure 1. Recorded signal from all five recording sites during a 20% MVC extension contraction. **a**, Erector spinae T_9; **b**, erector spinae L_3; **c**, erector spinae L_1; **d**, rectus abdominis; **e**, external oblique.

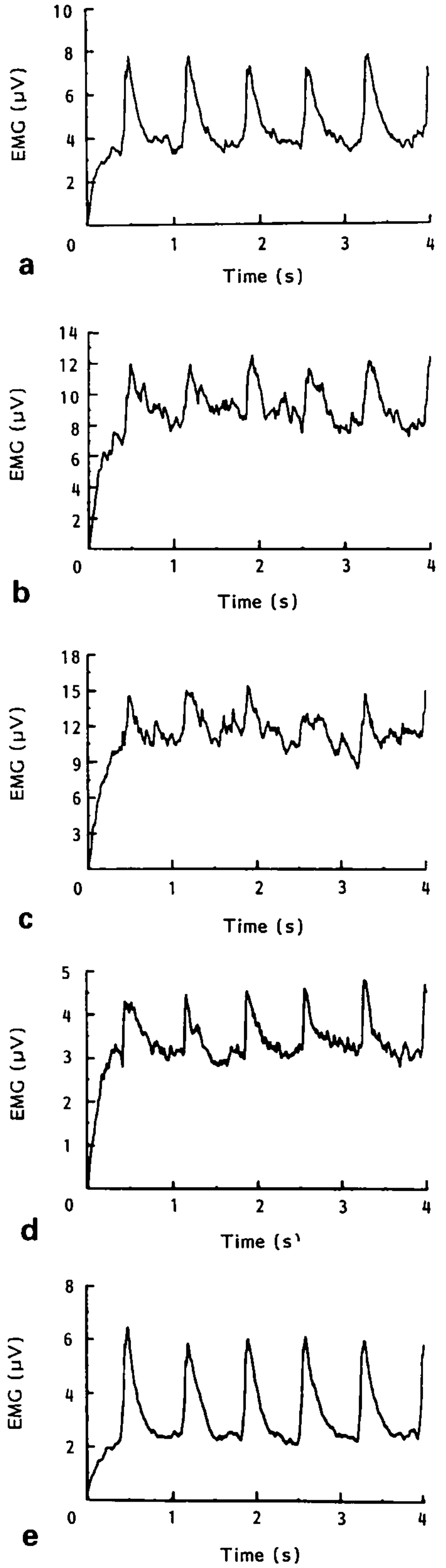

Figure 2. Integrated signals for the recordings shown in Figure 1. All integrations are performed without filtering. **a**, Erector spinae T_9; **b**, erector spinae L_3; **c**, erector spinae L_1; **d**, rectus abdominis; **e**, external oblique.

recording site. Some low-frequency motion artefact or drift is also seen throughout the signals. In these 20% MVC trials the ECG signals are at approximately the same amplitude as the EMG for the erector spinae muscles. The 0 and 10% MVC trials had lower EMG levels which brought out the ECG, while the higher load trial (40 and 100% MVC) had higher EMG levels than the ECG contamination for some of the erector spinae recordings. Similar results were seen for the rectus abdominis and external oblique muscle during the flexion trials.

Integration of the recorded signals sometimes showed large effects from ECG contamination. Figure 2 depicts the integrated signals from the recordings shown in Figure 1. The effect of ECG contamination on the erector spinae EMGs is greater for electrodes placed superiorly than for inferior locations. The rectus abdominis and external oblique, which are relatively quiet during these 20% MVC extensions, showed a pronounced ECG component during all extension trials.

To compare the relative contributions of ECG and EMG, a power spectral analysis was performed. Figure 3 compares the power spectra of the L_3 erector spinae data for a 20% MVC to an unloaded or 0% MVC trial. The spectrum of the unloaded trial is almost entirely due to the ECG signal. Note that most of the power in the ECG signal is below 30 Hz. The 20%

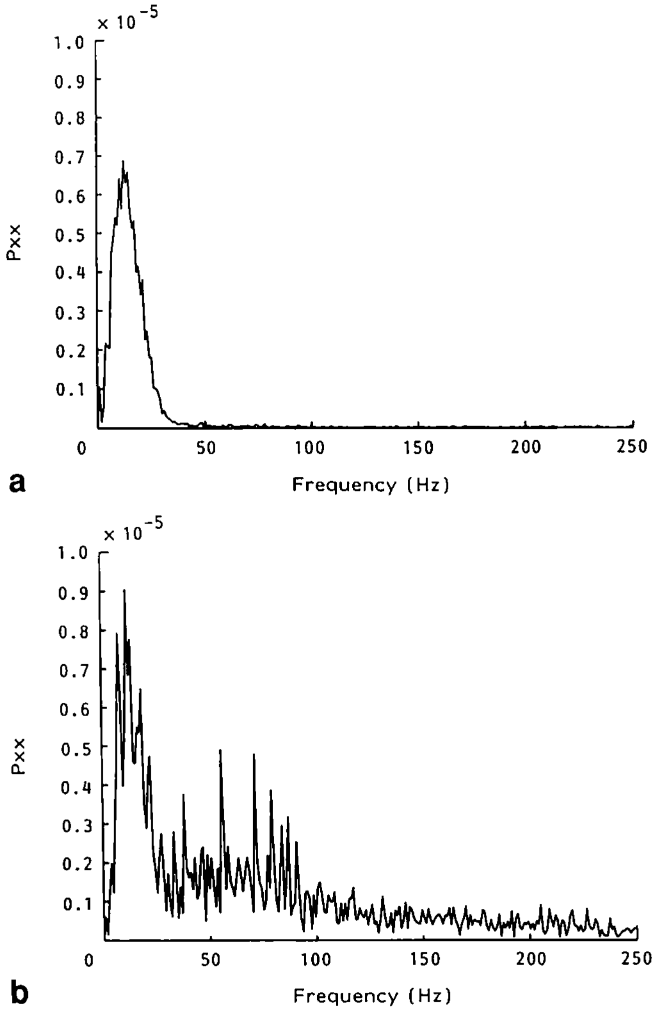

Figure 3. Power spectra for erector spinae signals including EMG and ECG contamination: (a) rest trial, and (b) 20% MVC flexion.

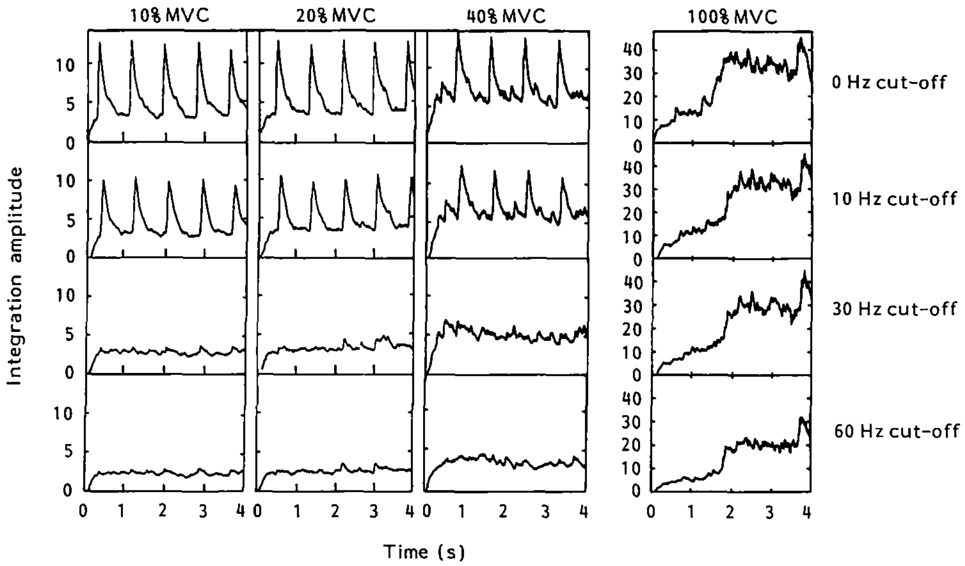

Figure 4. Integrated signals including EMG and ECG contamination of the erector spinae at the T_9 level, for 10, 20, 40, and 100 per cent MVC extensions. Integration was performed after high-pass filtering the EMG at 0, 10, 30, and 60 Hz.

MVC trial shows power, presumably from the EMG, over 40 Hz.

The recorded EMG signals were high-pass filtered with cut-off frequencies of 0, 10, 30, and 60 Hz and then processed with a digital integrator. Figure 4 shows the results of such processing on the T_9 erector spinae signal for the extension trials. The effects of the ECG contamination are pronounced in all but the 100% MVC trials, and reduced as the cut-off frequency is increased. The 30 Hz cut-off frequency eliminates most of the ECG effects from the integrated EMG in all extension contractions. Note the drop in amplitude of the integrated EMG as the cut-off is increased from 30 to 60 Hz. For all subjects, increasing the cut-off frequency affected the integrated signal in three ways: (1) decreasing the amplitude, (2) altering the shape, and (3) smoothing the response. These effects are due to the elimination of the low frequencies in the recorded signal. Similar results were found in filtering the signals from other sites. For example, filtering the rectus abdominis signal, which has a relatively high ratio of ECG to EMG, produced the same reduction in ECG contamination.

Power estimations

Power levels for the muscles both filtered and unfiltered were calculated and are presented in Table 1. The power estimates for the 0 per cent exertion level of each muscle are due to the ECG contamination of the signal and some small baseline EMG. In these recordings the baseline EMG was very small and believed to be insignificant, therefore these 0 per cent powers are assumed to be solely due to ECG. When the three filters were applied to these signals, similar percentage loss of power were seen. The 10 Hz filter produced a signal about 25 per cent that of the original ECG. The 30 Hz filter reduced the signal to between 4 and 10 per cent, while the 60 Hz filter reduced the power content to between 3 and 8 per cent. Thus there was a dramatic decrease in ECG contribution at the 10 Hz cut-off and 30 Hz cut-off; however the reduction going from 30 to 60 Hz was minimal.

In the power analysis, it was found that the ECG content of the signals at exertion levels greater than 10 per cent was relatively small. For example, the estimated ECG power for the EO at 20% MVC (18.4) is only one-tenth the total power (182.0). As compared to the 100 per cent MVC contraction, the ECG power was less than one-hundredth of the total power. The

Table 1. Power content for the recorded EMG signals, both filtered and unfiltered

Muscle	*Exertion (%MVC)*	*Signal Power*			
		Unfiltered	*10 Hz*	*30 Hz*	*60 Hz*
EO	0	18.4	5.9	2.4	1.5
EO	10	62.0	58.0	35.0	8.3
EO	20	182.0	177.0	125.0	24.6
EO	40	683.0	644.0	497.0	78.0
EO	100	2790.0	2770.0	2290.0	370.0
RA	0	2.2	0.5	0.2	0.1
RA	10	4.4	2.4	1.6	0.7
RA	20	17.0	15.0	12.0	4.1
RA	40	276.0	270.0	250.0	89.0
RA	100	333.0	327.0	295.0	89.0
ES	0	1.7	0.4	0.1	0.1
ES	10	2.9	1.6	1.1	0.8
ES	20	8.6	7.4	6.2	4.7
ES	40	24.0	22.0	20.5	15.0
ES	100	177.0	172.0	157.0	114.0

EO, external oblique; RA, rectus abdominis; ES, erector spinae.

diminishing effects of the ECG contamination on the output integrated EMG signals with an increase in exertion level is explained by this relative disparity between the ECG and EMG powers.

Discussion and conclusions

An increase in cut-off frequency reduces the variation in the integrated EMG signal. This reduction of variation is due not only to the removal of ECG and movement artefacts, but also to the filtering of the low frequencies in EMG signals. These lower frequencies of the EMG are therefore lost when the cut-off frequency is too high. This is important since most of the power in the EMG is found below 100 Hz. The choice of a cut-off does not appear to be critical, however, for observing changes in integrated EMG activity related to changes in exertion levels. The power analysis of this study indicated that the distribution of the EMG spectrum tends to remain constant as the force levels are changed. Thus, the relationship between EMG amplitude and exertion level will only vary by a constant multiplicative factor as the cut-off is altered.

Based on this study, high-pass filtering of torso EMG seems a good processing method to eliminate ECG contamination and motion artefact during isometric exertions, particularly if the recorded signal is to be further processed by integration, RMS, or some other technique. Caution should be exercized, however, in choosing an appropriate cut-off frequency. Important EMG information may be lost if the cut-off is unnecessarily high. The cut-off should be chosen by observing the spectrum of the ECG signal when the subject is at rest and determining its frequency bandwidth. A cut-off which eliminates most of the ECG power while keeping a majority of the EMG signal is optimal. In this study a cut-off frequency of 30 Hz was best of those examined. The power spectra of all the recording sites on the subjects tested suggested that the range of optimal cut-off frequencies was from 20 to 30 Hz.

One word of caution is that the data from this study is only appropriate for surface EMG recordings. Indwelling electrodes have a different impedance and would therefore have different frequency characteristics. In fact, other electrode types may also have different impedances. Variables such as electrode placement, electrode size, muscle size, and distance between electrodes will affect the spectrum of the signal as well[7]. Cross-talk from other muscles may also affect the EMG recording by adding to the low-frequency region of the signal[8]. Thus, a repeat of this procedure may be required to develop a cut-off level for high-pass filtering for indwelling electrodes and other types of surface electrodes. For typical silver–silver chloride surface electrodes, however, this study does indicate that a cut-off of between 20 and 30 Hz is best to remove ECG contamination from torso EMG signals.

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