Time Frequency Analysis of the Electromyogram During Fatigue

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Abstract

Spectral parameters obtained from the surface electromyogram (EMG) signal have been used as indicators of fatigue during a sustained contraction. A new technique, time frequency analysis, was applied to the EMG signal. This technique generates a continuos representation of the changing spectrum of the signal through time. Three types of time frequency distributions were applied to the EMG signal. As predicted, differences existed between the distributions. The amplitude differential from the first time slice of the distribution to the last was the smallest for the Short Time Fourier Transform. The Wigner-Ville distribution was spread out across the most frequencies. Walls appeared in the Choi-Williams distribution, but otherwise it was the most compressed. All the distributions displayed the expected spectral compression; however, more work is necessary to clarify the results.

Introduction

The electrical manifestation of the neuromuscular activation associated with a contracting muscle is called the electromyogram (EMG) signal (Basmajian and DeLuca, 1985). Action potentials, detected by an electrode, can be positive or negative; therefore, the instantaneous sum of motor unit action potentials has both positive and negative components. The resulting EMG signal is very noise-like in appearance.

Muscular fatigue, implies that as a contraction is held, the muscle is weakening through time until failure. This weakening is characterized by changes in physiological processes. This fatigue affects only individual muscles or groups of synergistic muscles performing the contraction.

Spectral analysis is a process that begins by transforming a signal from the time domain to the frequency domain. Using Fourier transform techniques, the frequency components of the non-periodic function are found. A plot of the frequency components is the frequency spectrum. The frequency spectrum shows the distribution of energy versus frequency for the original signal. By squaring the amplitude of the frequency spectrum, the power density spectrum (PDS) is produced.

If the Fourier transform is applied to consecutive time sections of the original EMG signal, multiple power density spectra will be produced. The power density spectrum of the surface myoelectric signal compresses towards the lower frequencies during a sustained muscle contraction (DeLuca, Sabbahi, Stulen, and Bilotto, 1983).

Time-frequency techniques are used to analyze signals where the frequency content of the signal changes with time, as is the case with muscle fatigue. In a traditional frequency spectrum, the spectrum shows all the frequencies present in the signal, but does not indicate when in time and for how much time the frequencies are present. A time-frequency distribution shows at what instants in time those frequencies are present. Time-frequency analysis uses the entire signal and applies the Fourier transform to overlapping sections in time to develop a joint density function that is dependent on both time and frequency. The notation for time frequency analysis used in this paper is:

$s(t)$ - original time signal
$S(w)$ - Fourier transform of original time signal
$S_t(f)$ - Short Time Fourier Transform distribution
$P_w(t,f)$ - Wigner-Ville distribution
$P_{ch}(t,w)$ - Choi-Williams distribution

A common type of time frequency distribution is the Short-Time Fourier Spectrum (STFT). This technique utilizes the basic definition of time-frequency. If time-frequency distributions look at the frequencies that exist during a certain time section of a signal, then one way to generate this distribution is to take a short time portion of the signal, apply the Fourier transform to it, and proceed to the next time section. At each time a different spectrum is obtained and the totality of these spectra is a time frequency distribution (Amin, Cohen and Williams, 1993). The equation representing this spectrum is:

$$S_t(f) = \int_{-\infty}^{\infty} e^{-j2\pi f\tau} s(\tau)\,d\tau \qquad (1)$$

In general, the STFT distribution works well unless there are very rapid fluctuations in the original signal (Amin, Cohen and Williams, 1993). The major difficulty with the STFT distribution is that it does not satisfy four important properties that are desired for time frequency distributions. The first two are the time and frequency marginals. They are not met because the windowing of the STFT changes the characteristics of the original signal. $P_1(t)$ and $P_2(w)$ would approach $|s(t)|^2$ and $|S(w)|^2$ respectively, as required if the windows in the respective domains were narrowed. Both windows cannot be narrowed simultaneously; therefore, the marginals cannot be satisfied (Amin, Cohen and Williams, 1993). Narrowing the window in time yields a poor frequency resolution, while a high frequency resolution is accompanied by a poor time resolution. The other two properties not satisfied are time and frequency support.

All time frequency distributions can be expressed in the same form, consisting of a kernel and the symmetrical ambiguity function. The STFT equation is clearer when not written in that form, but this form will be used for the other distributions in this paper. The general formula for these distributions is:

$$P(t,w) = \frac{1}{4\pi^2}\iiint e^{-j\theta t - j\tau w + j\theta u}\phi(\theta,\tau)\,s^*(u - \tfrac{1}{2}\tau)\,s(u + \tfrac{1}{2}\tau)\,du\,d\tau\,d\theta \qquad (2)$$

Within this formula, the symmetrical ambiguity function is:

$$\chi_s(\theta,\tau) = \int s^*(u - \tfrac{1}{2}\tau)\,e^{-j\theta u}\,s(u + \tfrac{1}{2}\tau)\,du \qquad (3)$$

while the kernel is represented by $\phi(\theta,\tau)$. For this paper, the equation was rearranged slightly:

$$P(t,w) = \frac{1}{4\pi^2}\iint e^{-j\tau w}\,r(u-t,\tau)\,s^*(u - \tfrac{1}{2}\tau)\,s(u + \tfrac{1}{2}\tau)\,du\,d\tau \qquad (4)$$

where $r(u,\tau) = \int e^{-j\theta u}\phi(\theta,\tau)\,d\theta \qquad (5)$

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The kernel is the portion of the equation which changes from one distribution to another. The kernel, therefore, defines which distribution is being used.

For the Wigner-Ville distribution, the kernel is one. The equation for this distribution is:

$$P_w(t,f) = \int_{-\infty}^{\infty} e^{-j2\pi f\tau} s^*\left(t - \tfrac{1}{2}\tau\right) s\left(t + \tfrac{1}{2}\tau\right) d\tau \qquad (6)$$

The joint density spectrum produced by the Wigner-Ville distribution is very noisy. When the original signal is the sum of two or more signals, cross terms are produced.

The Wigner-Ville distribution displays very good localization properties, and it is generally concentrated around the instantaneous frequency of the signal. However, when the signal evaluated is a multi-component signal, it displays the components of the individual frequencies, but it also displays the cross terms which are spurious (Amin, Cohen and Williams, 1993).

The third distribution used was the Choi-Williams distribution. The Choi-Williams is an example of a reduced interference distribution. The kernel for this distribution is:

$$\phi(\theta,\tau) = e^{-\frac{\theta\tau^2}{2}} \qquad (7)$$

The joint density spectrum is then defined as follows:

$$P_{cw}(t,w) = \frac{1}{4\pi^{3/2}} \iint \frac{1}{\sqrt{\tau^2/\sigma}} e^{-\frac{(u-t)^2}{4\tau^2/\sigma}} e^{-j\tau w} s^*\left(u - \tfrac{1}{2}\tau\right) s\left(u + \tfrac{1}{2}\tau\right) du\, d\tau \qquad (8)$$

Although the Choi-Williams distribution does not satisfy all the desired properties for a time frequency distribution, it does satisfy an important one, reduced interference.

Applying time frequency techniques to the EMG signal during muscle fatigue may add information that was not available using the traditional spectral analysis techniques.

Methods

Fifteen healthy male subjects between the ages of 28 and 38 were tested. Each subject came to two testing sessions with at least one week between sessions. At each of these sessions, fine wire and surface electrodes were used to record the EMG signal of the biceps brachii during an isometric contraction.

The digitized signals, containing the entire EMG signal, were loaded into Matlab, where they were analyzed using time-frequency analysis techniques.

The three time frequency distributions mentioned previously were used in this analysis portion: the Short Time Fourier Transform, the Wigner-Ville distribution and the Choi-Williams distribution.

The EMG signal was obtained from both fine wire and surface electrodes so that a study could be done comparing the spectral compression obtained from the two types of electrodes. In this paper, we will illustrate time frequency analysis with one example of fine wire EMG data.

Results

The three time frequency distributions were applied to the fine wire EMG signal. The results for subject 1, trial 3 are shown in Figures 1, 2, and 3.

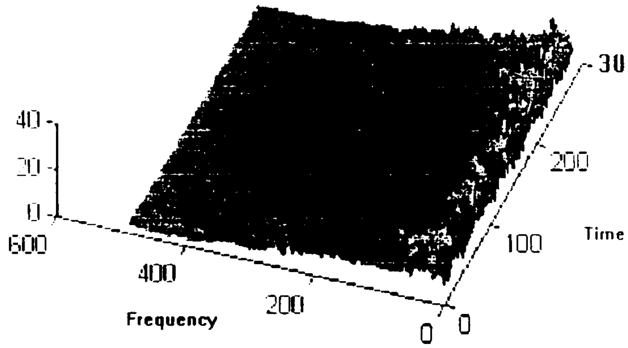

Figure 1 Time Frequency Distribution - Fine Wire EMG signal: STFT

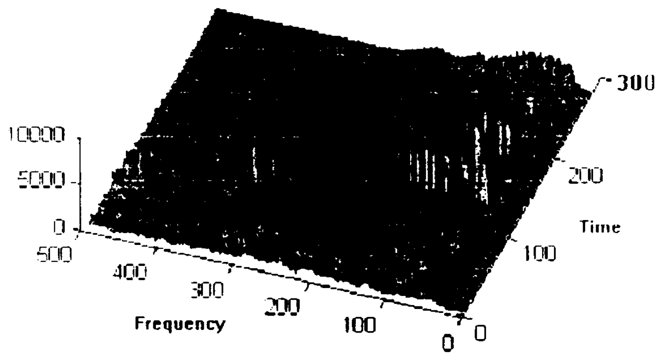

Figure 2 Time Frequency Distribution - Fine Wire EMG signal: Wigner-Ville

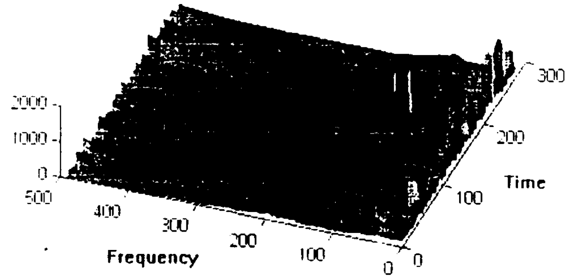

Figure 3 Time Frequency Distribution - Fine Wire EMG Signal - Choi-Williams

The three time frequency distributions produce very different distributions. The STFT distribution has very wide spectral components, and the only indication of spectral compression is a slight rise in amplitude at the end of the contraction. The Wigner-Ville distribution most clearly shows the spectral compression. At the beginning of that distribution the frequency components extend across the entire plotted frequency axis, and as time increases the distribution narrows to the lower frequency end. However the cross terms are not distinguishable from the true distribution of the signal. The Choi-Williams distribution indicates a spectral compression because the frequency spread is less as time increases and the amplitudes of the spectrum are higher at the lower frequencies. The walls, points in time where all frequencies exist, make this distribution difficult to interpret.

Discussion

A first attempt was made at applying time frequency techniques to the EMG signal during fatigue. In general, the results were good, showing the expected spectral compression with time of contraction.

The Short Time Fourier Transform appears to most clearly show the compression of the spectrum as the muscle fatigues. However, the STFT does not satisfy the marginal properties. This factor implies that when a time slice of the STFT distribution is taken, it does not equal the power density spectrum at that point in time. The same is true for a frequency slice of the distribution. The time support property is not satisfied because the distribution is not necessarily zero before the signal begins or after it ends. Furthermore, if the original signal is bandlimited, the STFT distribution may not be zero outside the band; therefore the frequency support property is not satisfied.

The Wigner-Ville distribution intrinsically has cross-terms and therefore is not a precise representation of the changing of the frequency components with fatigue.

The joint time-frequency densities obtained using the Choi-Williams distribution seem to most accurately show the frequency compression. The walls in the distribution (points in time when it appears that all frequencies exist) make this distribution hard to analyze. One possible theory for the presence of these walls is spikes in the original time signal. When walls appear in the Choi-Williams distribution there is a spike in the original signal. The Fourier transform of a spike is a line across all frequencies; a wall. The Choi-Williams distribution may be the only distribution that is sensitive enough to pick this up. It will be decided if the walls contain any significant information for the study of muscle fatigue. If they do not, the distribution can be smoothed across time to reduce their influence.

Suggestions for the Future

Time frequency techniques can be very sensitive to fluctuations in the signal, as was shown by the walls in the Choi-Williams distributions. If the fluctuations do not contain pertinent information for the study, they should be filtered out. Time frequency techniques require a very clean signal.

There are many other time frequency distributions. The STFT and Wigner-Ville distributions were chosen for this project, because they have been used widely in the past. Therefore, there are well understood and can be used as a basis for comparison. The Choi-Williams distribution was arbitrarily chosen from a group of reduced interference distributions. Different distributions will emphasize different properties of the joint time frequency density.

The graphs presented in this paper are pictures of the change in frequency components throughout the time of the signal. Nothing, as of yet, has been done to use the actual matrix from which the plots are made. Techniques should be developed to manipulate the data contained in the time frequency matrix. Numerical representations of fatigue , which are more objective than graphical representations, could be extracted from this matrix. These values may provide better estimates of fatigue than the traditional spectral parameters: mean and median frequency. One such numerical representation would be the instantaneous frequency. For every time slice, the instantaneous frequency could be calculated. This value may decrease with spectral compression in a way similar to the median frequency. If that did happen, a relationship would need to be found between the median frequency, obtained with traditional spectral analysis methods, and the instantaneous frequency.

References

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