

Standardized Evaluation of Techniques for Measuring the Spectral Compression of the Myoelectric Signal

Gregory C. DeAngelis

L. Donald Gilmore

Carlo J. DeLuca

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Standardized Evaluation of Techniques for Measuring the Spectral Compression of the Myoelectric Signal

GREGORY C. DEANGELIS, STUDENT MEMBER, IEEE, L. DONALD GILMORE, AND
CARLO J. DELUCA, FELLOW, IEEE

Abstract—A digital algorithm was designed to produce band-limited noise with adjustable median frequency and amplitude. This algorithm produces test signals with spectral characteristics typical of those of the surface myoelectric signals encountered in muscle fatigue studies. These synthesized signals provide the basis for standardized evaluation of the performance of various techniques which monitor the spectral compression of the myoelectric signal during muscle fatigue.

INTRODUCTION

AS a muscular contraction is sustained, the power spectrum of the myoelectric (ME) signal is compressed into lower frequencies. This spectral shift is associated with the accumulation of metabolic byproducts during a sustained contraction and is a convenient and reliable indicator of muscle fatigue [1]. The use of the spectral shift of the ME signal as a measure of muscle fatigue offers a potentially more objective assessment technique, compared to the more subjective clinical techniques based on measurements of contractile fatigue [2]–[8]. In 1981, Stulen and De Luca [9] reported the development of a noninvasive, analog device, the muscle fatigue monitor (MFM™), to calculate the median frequency parameter (f_{med}) of the ME power density spectrum during fatiguing contractions. As a result of their work and the continuing advancement of the MFM [10], other researchers have developed additional hardware and software techniques to monitor some parameter of the spectral shift of the ME signal during fatigue. Different hardware techniques, such as those described by Merletti *et al.* [11] and Petrofsky [12], have had varying degrees of success in measuring fatigue. Recently, due to advances in computer technology, software techniques using the fast Fourier transform (FFT) have also become popular tools for investigating spectral parameters [13].

Because many of the techniques for monitoring ME spectral shift use different principles of operation, some of these may be unsuitable for application to muscle contractions which exhibit complex spectral changes. For example, an analog hardware technique and an FFT-based software technique may compute differing median frequency values during a dynamic, fatiguing contraction in

which ME signal amplitude varies with muscle force output. Under these conditions, the FFT technique may be inappropriate due to nonstationarity of the ME signal, whereas the analog device may still provide valid median frequency estimates. While most fatigue monitoring techniques have been tested using sine waves or experimentally collected ME signals, there is no standardized method for evaluating and comparing their performance in response to signals which possess known complex spectral changes.

This paper presents an algorithm for simulating typical ME spectra, and provides an example of its usefulness in evaluating muscle fatigue monitors under conditions which simulate both static (constant force) and dynamic (variable force) contractions.

To a first approximation, the ME signal may be described as a Gaussian random process [14]–[16]. Stulen and De Luca [1] have modeled the ME signal as white, Gaussian noise passing through a linear filter. By varying the gain of the white noise source and the coefficients of the linear filter function, it is possible to synthesize signals having dynamic amplitude and frequency variations which are representative of the spectral changes typically observed in the ME signal during many fatiguing contractions. In this fashion band-limited noise can be preferentially useful for testing techniques that measure muscle fatigue parameters of the ME signal.

This paper describes the design and implementation of a white noise generator and signal processing system which creates band-limited noise with known median frequency (f_{med}) and amplitude variations. The noise generation algorithm described uses ramp, step, and sinusoidal variations in amplitude and/or f_{med} to mimic typical patterns of change in the ME power spectrum.

METHODS

Fig. 1 shows a block diagram for the simulated ME signal generation algorithm.

The fundamental components of the system are a random number generator, a second-order digital low-pass filter, and a filter function modulation algorithm, all of which are implemented on an IBM PC AT computer. The remainder of the system consists of a D/A converter and an analog bandpass filter with cutoffs at 20 and 500 Hz.

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The authors are with the NeuroMuscular Research Center, Boston University, Boston, MA 02215.
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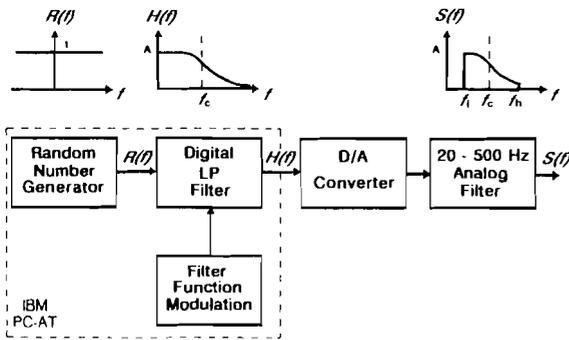


Fig. 1. A block diagram for the simulated ME signal generation algorithm, illustrating the basic system components as well as the shaping of the frequency spectrum.

Gaussian Random Number Generator

A computer algorithm, written in the Basic language, produces a normally distributed random number sequence with zero mean and unit variance, using the Box-Muller transformation. The random number generator seed can be fixed such that each sequence produced will be identical, or the generator may be seeded randomly using digits from the computer's internal clock. The Gaussian random sequence has a flat frequency spectrum, $R(f)$ (see Fig. 1), with a constant value equal to the variance; hence, the spectrum assumes the shape of the filter function used in the digital signal processing scheme.

Digital Low-Pass Filter

The random number sequence described above is digitally low-pass filtered using a second-order Butterworth filter, designed via the bilinear transformation technique. The second-order filter was chosen for its relative ease of implementation and simple frequency response function, $H(f)$ (see Fig. 1), which allows the median frequency to be expressed in terms of the low-pass cutoff frequency. Applying the bilinear transformation to a second-order Butterworth low-pass filter function, the digital filter function,

$$H(z) = \frac{A(z^{-2} + 2z^{-1} + 1)}{Bz^{-2} + Cz^{-1} + D} \quad (1)$$

is obtained. A is the dc gain of the digital filter; B , C , and D are constants at a particular sampling frequency; and z is the variable of the Z -transform. The digital filter was implemented as a difference equation in the Basic language.

D/A Converter and Analog Bandpass Filter

The filtered digital sequence is passed through a D/A converter, as depicted in Fig. 1. Following D/A conversion, the analog noise is bandpass filtered with sharp (36 dB/octave) cutoffs at 20 and 500 Hz, producing a truncated frequency spectrum $S(f)$ with the same bandwidth commonly used in processing surface ME signals, see Fig. 1. This truncation is necessary in order to confine the spectrum $S(f)$ to a known frequency band, such that the median frequency may be expressed in terms of the digital

low-pass filter cutoff frequency. Analog bandpass filtering was selected over digital bandpass filtering in order to simplify the implementation of this algorithm. To prevent distortion of the desired signal spectrum, a 2 kHz D/A conversion rate was chosen such that the frequency response of the D/A is virtually flat over the bandwidth from 20 to 500 Hz.

Filter Function Modulation Algorithm

Fig. 2 shows a schematic illustration of the magnitude of the power density spectrum $|S(f)|^2$ produced at the output of the system of Fig. 1. The shape and spread of the resultant synthesized signal around the median frequency approximates the De Luca-Stulen spectral model [1].

The cutoff (-3 dB) frequency of the digital low-pass filter is f_c . A is the dc filter gain, and f_{med} is the median frequency of $|S(f)|^2$. f_l and f_h are the lower and upper corner frequencies, respectively, of the analog bandpass filter. To produce band-limited noise with known median frequency variations, f_{med} must be related to the cutoff frequency f_c of the digital low-pass filter.

By equating the integral of $|H(f)|^2$ from f_l to f_{med} with one-half the integral of $|H(f)|^2$ from f_l to f_h , we obtain an expression for the frequency which divides $|S(f)|^2$ into halves of equal power; this is by definition the median frequency f_{med} . Using a standard table of integrals, this expression takes the following form:

$$\begin{aligned} & \ln \left\{ \frac{f_{med}^2 + f_c f_{med} \sqrt{2} + f_c^2}{f_{med}^2 - f_c f_{med} \sqrt{2} + f_c^2} \right\} \\ &= -2 \times \arctan \left\{ \frac{f_c f_{med} \sqrt{2}}{f_c^2 - f_{med}^2} \right\} + K + M \quad (2) \end{aligned}$$

where

$$\begin{aligned} K &= \frac{1}{2} \left\{ \ln \left(\frac{f_h^2 + f_h f_c \sqrt{2} + f_c^2}{f_h^2 - f_h f_c \sqrt{2} + f_c^2} \right) \right. \\ & \quad \left. + 2 \times \arctan \left(\frac{f_h f_c \sqrt{2}}{f_c^2 - f_h^2} \right) \right\}, \end{aligned}$$

and

$$\begin{aligned} M &= \frac{1}{2} \left\{ \ln \left(\frac{f_l^2 + f_l f_c \sqrt{2} + f_c^2}{f_l^2 - f_l f_c \sqrt{2} + f_c^2} \right) \right. \\ & \quad \left. + 2 \times \arctan \left(\frac{f_l f_c \sqrt{2}}{f_c^2 - f_l^2} \right) \right\}. \end{aligned}$$

Since a closed-form solution of (2) is not practical, this equation is solved iteratively in software. The resulting program, which computes the value of f_c given f_{med} , f_l , and f_h , is used to set the cutoff frequency f_c of the digital low-pass filter such that band-limited noise with a particular median frequency is obtained. Note that it is necessary to compensate for frequency warping induced by the use of the bilinear transformation so that accurate median

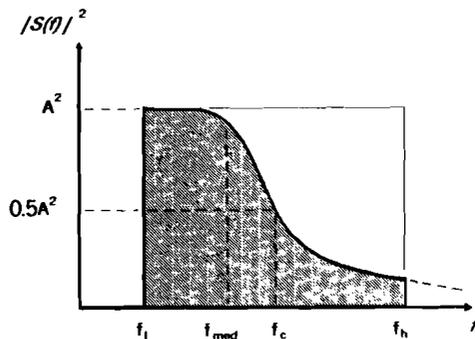


Fig. 2. Schematic illustration of the power spectrum $|S(f)|^2$ used to simulate actual ME spectra. A is the dc gain of the digital low-pass filter, f_l is the low-pass cutoff frequency, f_l and f_h are the lower and upper rolloff frequencies, respectively, of the analog band pass filter, and f_{med} represents the median frequency of $|S(f)|^2$.

frequencies will be produced. The s -domain frequency variable f is related to the z -domain frequency variable w by the expression.

$$w = \frac{2}{T} \arctan\left(\frac{fT}{2}\right) \quad (3)$$

where T is the sampling period of the D/A converter.

Median frequency variations are synthesized by adjusting the cutoff frequency f_c of the digital filter; spectral compression of the output signal may be simulated by decreasing f_c while maintaining f_l constant. Amplitude variations may be achieved by simply modulating the dc filter gain A in some desired fashion (i.e., step-wise, sinusoidally, etc.).

In this manner, a variety of amplitude patterns can be synthesized without affecting the median frequency, provided that the rate of amplitude modulation does not introduce significant frequency components into the power spectrum of the simulated ME signal. This restriction requires that amplitude variations do not exceed a frequency of 20 Hz.

The controlling software for the simulated ME signal generation algorithm is menu-driven and allows the user to select the type of amplitude variation (constant, step, ramp, sinusoidal) and the type of median frequency variation (constant, step, ramp). In addition to these options, the menu could be expanded to include virtually any type of variation which is useful for simulating the spectral characteristics of the ME signal. Prior to D/A conversion, the digital form of the signal may be stored on floppy disc for later use or for digital analyses. Following D/A conversion and bandpass filtering, the signal may be recorded on analog tape for testing of analog equipment.

Testing the Simulated ME Signal Generation Algorithm by FFT

In order to test the accuracy of the signal generation algorithm, five constant amplitude (filter gain = 1), constant f_{med} digital test signals, each at a different median frequency between 50 and 150 Hz, were created. This was reported for different values of the dc filter gain. A fast Fourier transform (FFT) algorithm was used to analyze

TABLE I
ACCURACY TEST RESULTS COMPUTED BY FFT

Predicted f_{med} (Hz)	Computed f_{med} (Hz) using FFT (mean value \pm standard deviation)
50	49.1 \pm 2.6
80	80.8 \pm 3.2
100	101.0 \pm 3.3
120	119.4 \pm 3.1
150	149.3 \pm 3.3

Median frequency estimates produced by fast Fourier transform for five constant f_{med} simulated ME signals, each with a different median frequency value and a fixed amplitude. Each FFT value represents the average from ten 1 s windowed segments, plus or minus the standard deviation in hertz.

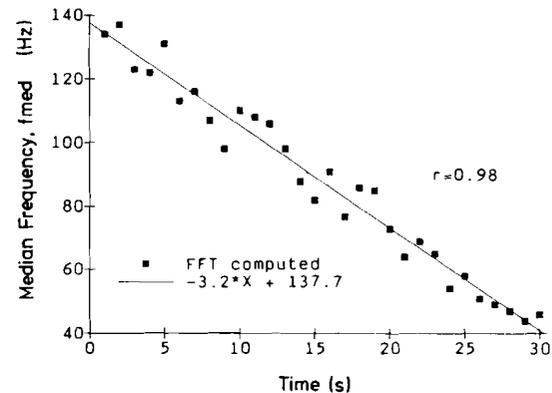


Fig. 3. FFT analysis of a 30 s f_{med} ramp from 140 Hz down to 40 Hz. Each FFT value (solid squares) represents the median frequency estimate of a 1 s windowed epoch. The regression line (autocorrelation coefficient, $r = 0.98$) closely resembles the theoretical 140-40 Hz ramp.

each of the signals, employing a 2048-point (1 s) window. Median frequency values were computed by FFT over ten consecutive 1 s windowed segments.

To test linearity, a 30 s constant amplitude median frequency ramp from 140 down to 40 Hz was generated. This was done by ramping the cutoff frequency of the digital low-pass filter between the appropriate endpoints, computed using equation (2). Again, the digital data file was analyzed by FFT and median frequency values were computed over consecutive 1 s windows.

RESULTS

Table I shows median frequency values computed by FFT for five constant median frequency simulated ME signals, with f_{med} values as predicted by the mathematics of the previous section. Each f_{med} value in Table I represents the average f_{med} from ten 1 s windowed segments plus or minus the standard deviation in Hertz.

In each case, the computed value differs by less than 2% from the predicted value. Furthermore, some of this error may be attributed to the 1 Hz spectral resolution that comes with using a one second window. Similar accuracy is obtained for different values of the low-pass filter gain, so that Table I represents results which are valid for all noise amplitudes within the dynamic range of the D/A converter (± 40 mV to ± 5 V).

Fig. 3 shows the FFT analysis of a 30 s duration, con-

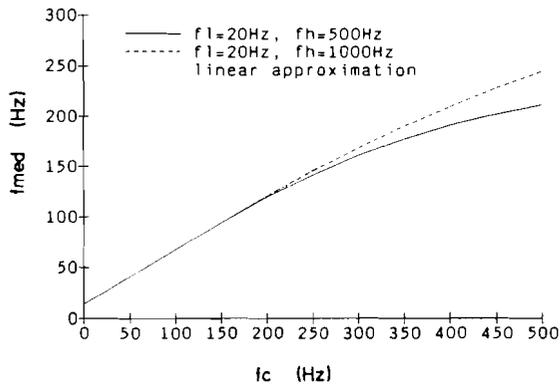


Fig. 4. Graphical relationship between cutoff frequency f_c and median frequency f_{med} as given in (2). Increasing the high frequency cutoff of the analog BP filter extends the linear range of this relationship to some extent.

stant amplitude 140–40 Hz median frequency ramp produced by the algorithm of Fig. 1. Median frequency values are computed by FFT over 30 consecutive 1 s windowed intervals, and plotted along with the regression line. The FFT points are clustered closely about the regression line ($r = 0.98$), and the regression line closely approximates the desired median frequency ramp.

Fig. 4 shows the relationship [see (2)] between the digital filter cutoff frequency f_c and the median frequency f_{med} of the simulated ME power spectrum. For $f_l = 20$ Hz and $f_h = 500$ Hz (solid line, Fig. 4), this relationship may be considered linear for median frequencies as high as 140 Hz, as the curve deviates by no more than 4 Hz from the linear approximation (dotted line). By increasing f_h to 1000 Hz (dashed line), the relationship becomes essentially linear for f_{med} up to 170 Hz.

DISCUSSION

Evaluation of techniques and devices which measure the spectral shift of the ME signal requires test signals that simulate the changes which typically occur in the ME power spectrum during muscle fatigue. Sine wave analyses can be useful in assessing the accuracy of the devices but cannot reveal deficiencies induced by the stochastic nature of the ME signal. Empirical tests using raw myoelectric data allow comparison of different fatigue measuring techniques under realistic conditions, but do not provide objective analytical results since the ME signal spectra are not known *a priori*. For these reasons, a more objective, standardized method of testing, which considers both the spectral and temporal characteristics of the ME signal, is required.

The technique described in this paper addresses both spectral and temporal characteristics by generating simulated ME signals with known median frequency and amplitude variations. Test results reveal that, by controlling these two signal parameters, the suggested approach is useful for modeling ME power spectra encountered during fatigue studies. The results of the FFT analyses displayed in Table I show that the simulated ME signal gen-

eration algorithm yields accurate median frequencies, independent of signal amplitude. Moreover, the relationship between the digital filter cutoff frequency f_c and the median frequency f_{med} may be considered linear for f_{med} up to at least 140 Hz. Since the median frequency of ME power spectra seldom exceeds 140 Hz, many useful median frequency trajectories may be created in band-limited noise by simply specifying a desired variation in f_c . Linearity may be further improved by choosing a larger value of f_h , so that spectrum truncation is reduced (see Fig. 4). If necessary, the D/A sampling time may be reduced such that the frequency response of the D/A does not reshape the desired spectrum.

Implementation of this digital signal generation algorithm, as a complement to simple sine wave tests and non-specific ME signal tests, provides a standardized, comprehensive, and objective means to evaluate and compare the performance of almost any technique that measures ME spectral shifts. A complete performance evaluation involves testing a device or algorithm (such as the MFM) under conditions which simulate many commonly encountered muscle contractions, whether constant or variable force, fatiguing, or nonfatiguing. A comprehensive evaluation protocol should test performance in response to a group of simulated ME signals which represent all these types of contractions.

We suggest a protocol involving at least the following four types of simulated ME signals, each of which possesses spectral characteristics which simulate a particular type of muscle contraction. Constant amplitude, constant median frequency noise represents the ME signal from a constant force, nonfatiguing contraction, and is useful for measuring accuracy under static conditions. Constant amplitude noise with a decreasing median frequency ramp simulates a fatiguing, constant-force contraction and may be used to evaluate performance in response to varying rates of muscle fatigue. Similarly, noise with a constant f_{med} and a sinusoidal amplitude variation allows one to mimic the ME signal associated with a cyclic force, non-fatiguing contraction. This test is useful in illuminating the effects of dynamic amplitude changes on median frequency computation accuracy. Finally, the combination of a sinusoidal amplitude variation and a decreasing median frequency ramp simulates the ME signal encountered during cycle force, fatiguing contractions. Although typical experimental values for median frequency and signal amplitude can deviate from these idealized situations, this standard evaluation protocol facilitates the objective, systematic testing of almost any technique which monitors a spectral parameter of fatigue, such as median frequency. While the four tests described above comprise a practical, comprehensive testing protocol, the signal generation algorithm can also create many other useful parameter variations, including median frequency and amplitude steps. Moreover, the mathematics of the algorithm could be modified to accommodate devices which measure other parameters of the ME power spectrum, such as the mean frequency.

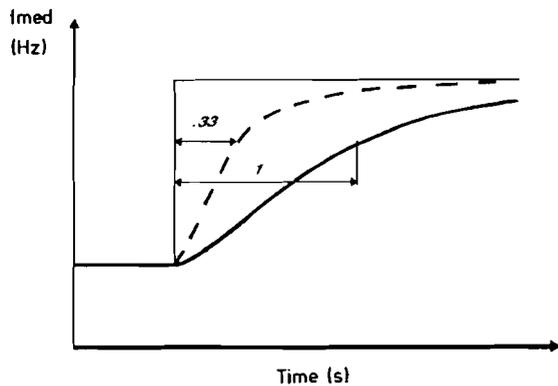


Fig. 5. Representative median frequency step responses produced by the MFM™, revealing that the median frequency tracking servo loop time constant is different for sine wave (dotted line) and band-limited noise (solid line) inputs.

The standard testing protocol introduced here has been used to evaluate the analog signal processing circuitry used by the MFM developed at the NeuroMuscular Research Center. Among the tests conducted were an evaluation of the speed of the median frequency tracking servo loop and an assessment of median frequency computation accuracy during variable amplitude signals. In the former test, servo loop tracking speed was analyzed in response to median frequency steps and ramps. The step response was obtained using constant amplitude noise with a f_{med} step and compared with the step response obtained using sine waves with the same frequency transition. For a given frequency step, the median frequency output of the MFM shows a servo loop time constant of approximately one-third second for the sine wave input (dashed line, Fig. 5) and a loop time constant of about 1 s for the noise input (solid line, Fig. 5).

This time constant disparity may be attributed to the broad band, stochastic nature of the simulated ME signal, in that the median frequency servo loop circuitry must average many quasi-randomly occurring spectral components in order to estimate the median frequency accurately. In order to determine an appropriate time constant for the servo loop, it is important to perform tests using band-limited noise, since the simulated noise spectrum offers a better approximation to the actual ME spectrum than does the line spectrum of a sine wave.

Median frequency computation accuracy was tested in response to simulated ME signals with dynamic amplitude characteristics. Fig. 6 shows median frequency traces computed by both the MFM (solid line) and FFT (dotted line) in response to band-limited noise with a decreasing median frequency ramp from 140 Hz down to 90 Hz and a sinusoidal amplitude variation. The MFM and FFT responses are well-correlated ($r = 0.76$), though the MFM trace lags behind the FFT trace by about 1 s due to the time constant of the median frequency tracking servo loop. Below a threshold level in rms amplitude, both the MFM and FFT responses exhibit relatively large deviations from the idealized ramp response. This may be partially attributed to decreased signal-to-noise ratio. These deviations

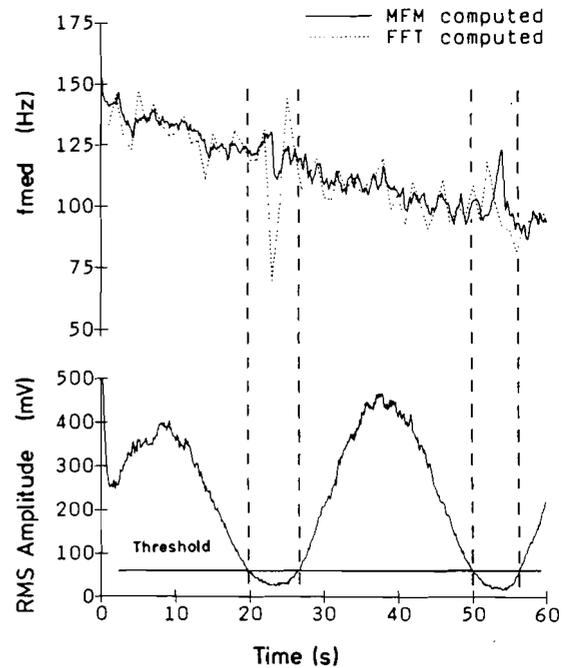


Fig. 6. Median frequency tracking evaluation in response to simulated ME signals with dynamic amplitude variations.

are less pronounced in the MFM response due to averaging effects of the analog servo loop time constant. This relative insensitivity to signal amplitude changes makes the MFM's analog servo loop technique applicable to investigations of fatigue under conditions encountered in dynamic contractions.

Use of this standard evaluation protocol has been valuable in revealing and correcting deficiencies in the dynamic performance of muscle fatigue monitor circuitry which may not have been detected otherwise. Based on the productive results which have been obtained in our laboratory, we feel that this evaluation protocol, which is based upon the noise generation algorithm, is an effective tool for standardized testing of many techniques that measure spectral parameters of the ME signal.

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L. Donald Gilmore was born in Boston, MA, in 1946. He received the A.B.E.E. degree in electrical engineering from Wentworth Institute of Technology, Boston, MA, in 1969.

Since 1970, he has held research positions at Liberty Mutual Research Center, Hopkinton, MA, and presently holds a faculty appointment at the NeuroMuscular Research Center, Boston University, Boston, MA. He has published in the area of electrophysiological properties of nerve tissue and the development of interfaces to record neuroelectric signals from peripheral nervous tissue. His current research interest centers on instrumentation techniques used to determine spectral parameters from myoelectric signals.



Carlo J. De Luca (S'64-M'72-SM'77-F'86) was born in Italy in 1943. He received the B.A.Sc. degree in electrical engineering from the University of British Columbia, Vancouver, B.C., Canada, in 1966, the M.Sc. degree in electrical engineering from the University of New Brunswick, Fredericton, Canada, in 1968, and the Ph.D. degree in biomedical engineering from Queen's University, Kingston, Ont., Canada, in 1972.

He is the founder and Director of the NeuroMuscular Research Center at Boston University which consists of a staff of approximately 25 professionals. He joined Boston University in September 1984. In 1986, he became Chairman ad interim of the Biomedical Engineering Department. From 1986-1989, he was the Dean ad interim of the College of Engineering while maintaining the Directorship of the NeuroMuscular Research Center. Prior to moving to B.U., he held faculty appointments at Harvard Medical School and MIT. He has been a consultant of long standing for the Liberty Mutual Research Center. He is the coauthor of the book *Muscles Alive*, and has published 67 articles and approximately 120 abstracts. His research interests span motor control, rehabilitation medicine and engineering, low back pain, and muscle fatigue.

Dr. De Luca is the elected President of the Int. Soc. of Electrophysiological Kinesiology. He maintains various positions on the editorial board of several journals and scientific review committees. In 1989, along with two co-workers, he received the Volvo Award on Low Back Pain. He is the subject of several biographical references including *Who's Who in America* and *Who's Who in the World*.



Gregory C. DeAngelis (S'88) was born in Fairfield, CT, in 1965. He received the B.S. degree in biomedical engineering from Boston University, Boston, MA, in 1987.

He is currently pursuing the doctoral degree at the University of California, Berkeley/San Francisco Joint Bioengineering Graduate Group. His research interests include signal processing in the visual system, motor control and muscle fatigue.

Mr. DeAngelis is a member of Tau Beta Pi, the Society for Neuroscience, and the Association for

Research in Vision and Ophthalmology.