Do the Firing Statistics of Motor Units Modify the Frequency Content of the EMG Signal During Sustained Contractions?

C.J. De Luca and J.L. Creigh
Boston University, Boston, Massachusetts, USA

It is well known that during sustained muscle contractions, the power density spectrum of the EMG or myoelectric signal detected with surface electrodes displays a frequency shift toward the low-frequency end. The high-frequency components decrease and the low-frequency components increase in amplitude. During the past two decades, various studies have attempted to determine whether the cause of the frequency shift originated from "physical properties" of muscle fibers, such as conduction velocity, or from "control properties," such as firing statistics. This question was investigated by deriving mathematical expressions for the power density spectrum of the myoelectric signal which contained separate functions expressing the individual effect of the firing statistics and the shape of the motor unit action potentials.

Model

The myoelectric signal may be considered to consist of a superposition of individual motor unit action potential trains (MUAPTs). Hence, the power density spectrum of the myoelectric signal may be expressed as:

$$S_m(\omega) = \sum_{i=1}^{p} S_{u_i}(\omega) + \sum_{\substack{i,j=1\\ i\neq j}}^{q} S_{u_i u_j}(\omega) \qquad (1)$$

where $S_{u_i}(\omega)$ = the power density of the MUAPT, $u_i(t)$
$S_{u_i u_j}(\omega)$ = the cross-power spectrum of MUAPTs $u_i(t)$ and $u_j(t)$
p = the total number of MUAPTs in the ME signal
q = the number of MUAPTs with correlated discharges.

For each individual MUAPT, the power density spectrum may be expressed as:

$$S_{u_i}(\omega) = S_{\delta_i}(\omega) \bullet |H_i(j\omega)|^2 \qquad (2)$$

where $S_{\delta_i}(\omega)$ = power density spectrum of the interpulse intervals
$H_i(j\omega)$ = the Fourier transform of the motor unit action potential.

It is well known that the time duration of motor unit action potentials increases during sustained contractions (Broman, 1973; De Luca & Forrest, 1973). This modification in the motor unit action potential is directly linked to the decreasing conduction velocities in the muscle fibers. Lindstrom (1970) has shown via a mathematical model that a decrease in the conduction velocity will cause a frequency shift (towards lower frequencies) of the function $H_i(j\omega)$. The question that now arises is: do the firing statistics of the MUAPTs also cause a modification in the power density spectrum of the myoelectric signal? In other words, are there features of the individual $S_{\delta_i}(\omega)$ that vary with the interpulse intervals (IPI) statistics and that are reflected in the overall spectrum when the $S_{\delta_i}(\omega)$s are combined?

Methods and Results

This point may now be verified empirically. By using the computer assisted decomposition technique developed by LeFever and De Luca (1982) and Mambrito and De Luca (1983), it is possible to obtain highly accurate IPI measurements of MUAPTs many seconds long. The Fourier transform of the IPIs may then be computed directly. Figures 1 and 2 each present the magnitude of such Fourier transforms for three

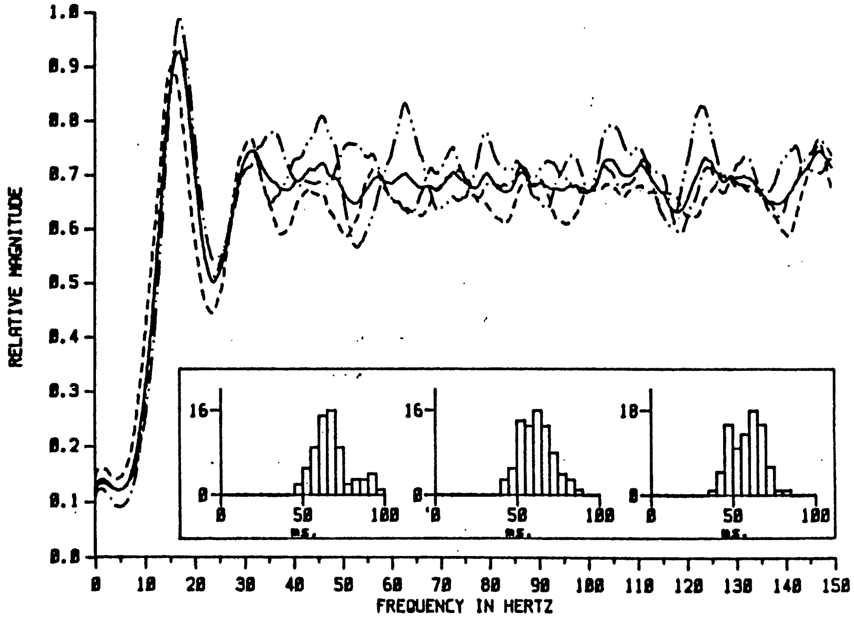

Figure 1—Fourier transform for three MUAPTs.

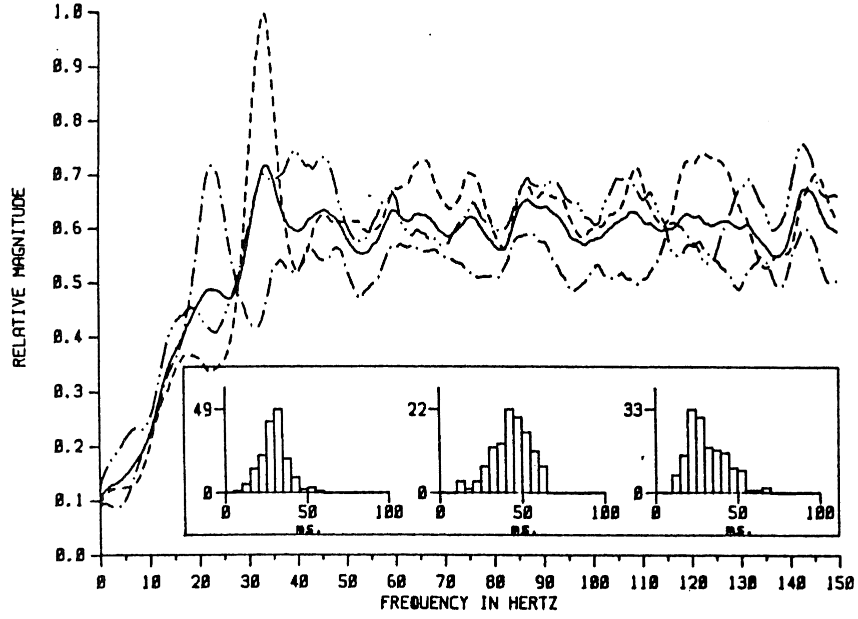

Figure 2—Fourier transform for three MUAPTs.

MUAPTs detected during two separate isometric constant-force contractions maintained at 50% of maximal force in the first dorsal interosseous muscle. The function with the solid line represents the average. The histograms present the IPI distribution of each motor unit, the one on the left corresponding to the function with the broken line and the middle histogram to the function with the dash-dot line. Some statistics of the IPIs are presented in the accompanying table. The coefficient of variation which is the ratio of the standard deviation to the mean value is a measure of the regularity with which the motor unit is discharging. The smaller the coefficient of variation, the sharper and higher will be the peak corresponding to the firing rate in the magnitude of the Fourier transform.

Table 1

Interpulse Interval Statistics

	μ (ms)	s.d. (ms)	c.v.
Figure 1	58.5	9.3	0.20
	61.8	10.0	0.16
	69.3	13.7	0.16
Figure 2	29.7	8.3	0.28
	31.3	11.8	0.38
	43.4	11.2	0.26

Discussion

When the coefficient of variation of the IPIs is small (0.16 to 0.20), the peak associated with the firing rates is clearly distinguishable (see Figure 1), whereas, when the coefficient of variation is higher (0.26, 0.28), then peak is less sharp and has lower amplitude (see Figure 2). The combined effect of the sharpness of the peak (due to the coefficient of variation of the IPIs) and the location of the peak (due to the value of the average firing rate) determines the extent to which a peak is present in the average Fourier transforms. (Compare Figures 1 and 2.)

It should be noted that the two parameters that have been identified as affecting the presence of the firing rate peak are both related to synchronization. That is, the smaller the coefficient of variation and the closer the average firing rate values, the greater the probability of two or more motor units discharging during a specific time interval. It should also be added that physiological events may also occur that may render the MUAPTs dependent and thereby introduce a third parameter to the concept of synchronization.

Also note that in either case the value of the magnitude of the Fourier transform is essentially constant beyond 40 Hz. The fluctuations beyond this point are due to the random nature of the IPIs.

The examples presented in Figures 1 and 2 indicate that the pattern and possibly the energy content of the power density spectrum of the myoelectric signal below 40 Hz may be altered by the statistics of the discharge properties of the motor units. Note that the average spectra shown do not take into account the shaping effects of the $H_i(j\omega)$ on each $S_{\delta_i}(\omega)$, but assuming that the motor unit action potential shapes are independent of the MUAPTs, the average shown is a useful representation of the effect of combining several trains. Although the effect below 40 Hz is not necessarily consistent, it cannot be overlooked when one attempts to identify the causes of the frequency shift of the myoelectric signal during sustained contractions, for it is known that the firing rates and other statistical properties of MUAPTs are time dependent during sustained contractions (De Luca & Forrest, 1973).

Acknowledgment

This work was supported by Liberty Mutual Insurance Company.

References

BROMAN, H. (1973). *An investigation on the influence of a sustained contraction on the succession of action potentials from a single motor unit.* Unpublished doctoral dissertation, Chalmers University of Technology, Gotenberg, Sweden.

DE LUCA, C.J., & Forrest, W.J. (1973). Some properties of motor unit action potential trains recorded during constant-force isometric contractions in man. *Kybernetic,* **12**, 160-168.

LeFEVER, R., & De Luca, C.J. (1982). A procedure for decomposing the myoelectric signal into its constituent action potentials: Part I—Technique, theory and implementation. *IEEE Transactions on Biomedical Engineering,* **29**, 149-157.

LINDSTROM, L. (1970). *On the frequency spectrum of EMG signals*. Unpublished doctoral dissertation, Chalmers University of Technology, Gotenberg, Sweden.

MAMBRITO, B., & De Luca, C.J. (1983). Acquisition and decomposition of the EMG signal. In J.E. Desmedt (Ed.), *New Developments in EMG and Clinical Neurophysiology*, **10**, 52-72.

On Adaptability of the Motor Program Model for Human Locomotion

A.E. Patla
University of Waterloo, Waterloo, Ontario, Canada

T.W. Calvert
Simon Fraser University, Burnaby, British Columbia, Canada

Human locomotion, which involves selective or combined muscular recruitment, control of equilibrium, and adaptation to the external environmental conditions (Nashner, 1980), is characterized by a stable, stride-to-stride repeatable pattern of muscular activation (Arsenault, 1982), joint torque patterns (Herman, Wirta, Bampton, & Finley, 1976; Winter, 1982), and joint kinematic patterns (Herman et al., 1976; Shapiro et al., 1981; Winter, 1982). The evidence from these and other studies strongly suggests the presence of a motor program for locomotion in humans. The relative invariance of the support moment when compared to the individual joint moments (Winter, 1982) and the phase dependent response in which the movement of the whole limb alters in character in response to an external stimulus (Patla & Belanger, 1983) suggests that the limb is controlled as an independent unit. This intralimb motor program is similar to the autonomous spinal locomotor generator for a limb in mammals such as cats (e.g., Grillner, 1975).

For it to be useful, the basic pattern for propulsion must be adaptable to different speeds of locomotion. Many studies have attempted to characterize changes in average EMG activity (e.g., Brandell, 1977), joint torque patterns (e.g., Winter, 1982), and joint kinematic patterns (e.g., Shapiro et al., 1981) with speed of locomotion. These studies, along with the evidence for the motor program for human locomotion, have been descriptive in nature. Besides, as noted by many researchers (e.g., Bekey, Chang, Perry, & Hoffer, 1977), the motor program is characterized not only by the individual EMG pattern, or joint torque and kinematic pattern, but also the interaction between these patterns.

The focus of this paper is to use an analytical model for the mammalian locomotor pattern generators proposed by Patla (1982) to model the locomotor motor program in humans and study its adaptability to varying speeds of locomotion. In this study, the joint kinematic patterns are used as a measure of the locomotor motor program; these can be viewed as the locomotor motor program output after it has been passed through the musculoskeletal transfer function. Since the model can be used with the