Power Spectral Analysis of Surface Electromyograms during Isometric Contractions

Haruhiko SATO
Department of Ergonomics, Kyushu Institute of Design

Abstract The power spectra of the bipolar surface EMG during isometric contractions for various human skeletal muscles were obtained for the frequency range from 6 to 378 Hz by the autocorrelation and its Fourier transformation technique. The effect of small movement artifact appeared in the frequencies below 10 Hz and the effect of the ECG around 15 Hz. Although there were some variations in the EMG power spectra of a muscle among subjects, there existed different EMG power spectrum patterns for different muscles. The significant energy of the EMG was within a frequency range approximately from 10 to 200 Hz in the biceps brachii, triceps brachii, brachioradialis, pectoralis major, vastus medialis and lateralis, tibialis anterior, deltoid and rectus femoris with some variations among these muscles. On the other hand, the power spectra of the gastrocnemius, masseter and frontalis were broadened and they had also significant energy above 200 Hz.

INTRODUCTION

Functional difference observed between human skeletal muscles which reflects man's physical characteristics is one of the important subjects in physical anthropology. Frequency analysis of electromyographic (EMG) signals has been used to aid in the understanding and investigation of muscle functions. The frequency spectra of the EMG have been studied concerning the electrode conditions and the states of muscle contractions (FEX & KRAKAU, 1958; NIGHTINGALE, 1959; HAYES, 1960; KOGI & HAKAMADA, 1962a; KAISER & PETERSÉN, 1963; SATO, 1964 and SATO & TSURUMA, 1967), the muscle fatigue (KOGI & HAKAMADA, 1962a, 1962b; SATO, 1965; KADEFORS et al, 1968; OKADA et al, 1970 and LLOYD, 1971), the effect of cooling (HAYAMI et al, 1967), the effect of alcohol (KIKUCHI, 1968) and the functional differentiation of skeletal muscles (KONDO, 1960; SATO et al, 1965; KONDO et al, 1968 and SATO et al, 1968). A certain amount of attention has been given to the frequency spectra of the EMG in the clinical diagnosis (WALTON, 1952; GERSTEN et al, 1965; KOPEC & HAUSMAN-PETRUSEWICZ, 1966; CHAFFIN, 1969 and SHIGIYA et al, 1973) and the myoelectric control of prostheses (SCOTT, 1967 and KWATNY et al, 1970).

The interference pattern or global EMG led by surface electrodes or subcutaneous electrodes (needle or wire electrodes) is a summation of action potentials of nume-
rous motor units. Frequency analysis is based on the fact that many complex wave forms can be characterized as the sum of regular sine waves. Frequency analysis of the EMG has been made usually by the band pass filter technique. This technique is simple and rapid, but it cannot determine the slope within a bandwidth and there is no standardization concerning the number and the bandwidths of filters.

The other technique is the autocorrelation and its Fourier transformation technique yielding power spectrum which has been developed in the communication engineering (Blackman & Tukey, 1958; Lee, 1960 and Box & Jenkins, 1970). If f(t) is a random function, its autocorrelation function \( \phi(\tau) \) is given by

\[
\phi(\tau) = \lim_{T \to \infty} \frac{1}{T} \int_{-T/2}^{T/2} f(t)f(t+\tau)dt
\]

where \( \tau \) is the lag time.

Since the autocorrelation function is an even function of \( \tau \),

\[
\phi(-\tau) = \phi(\tau)
\]

The autocorrelation function \( \phi(\tau) \) and the power spectral density function \( P(f) \) of the random function are related to each other by a Fourier cosine transformation as given by (3) and (4).

\[
\phi(\tau) = \int_{-\infty}^{\infty} P(f) \cos 2\pi ft df
\]

(3)

\[
P(f) = \int_{-\infty}^{\infty} \phi(\tau) \cos 2\pi ft d\tau
\]

(4)

where \( f \) is the frequency.

Therefore the autocorrelation and its Fourier transformation technique requires calculation of the autocorrelation function of the EMG and its subsequent Fourier transformation. The resulting spectral curve represents power density as a function of frequency.

The purpose of this paper are to evaluate the usefulness of the autocorrelation and its Fourier transformation technique in the frequency analysis of surface EMG and to obtain the EMG power spectra for various muscles of normal subjects.

**METHODS**

The subjects were eight normal males ranging in age from 21 to 25 years. The biceps brachii was examined for seven subjects, gastrocnemius for six, deltoid, pectoralis major, brachioradialis, frontalis and masseter for four and triceps brachii, rectus femoris, vastus medialis and lateralis and tibialis anterior for three. Some muscles were examined twice for the same subject on different days. The isometric contractions were performed without a special apparatus from a practical viewpoint. The subject contracted the biceps and triceps brachii against a load applied to the wrist downwards and upwards respectively with the elbow at 90° angle and the forearm horizontally in supination. The contraction of the brachioradialis was performed like the case of the biceps brachii, but with the forearm thumb-up position. The subject abducted the arm horizontally with the elbow extended and the forearm pronated, and contracted the deltoid against a load suspended from the distal end of the upper arm. The pectoralis major was contracted against a load applied horizontally at the distal end of the upper arm with the arm flexed horizontally, the elbow extended and the wrist held in the neutral position. The subject
was seated and contracted the rectus femoris, vastus medialis and lateralis against a load suspended from the ankle with the knee extended and the thigh held horizontal. The subject was seated with the feet held above the floor and contracted the tibialis anterior and gastrocnemius against a load applied to the metatarsal region downwards and upwards respectively with the knee angle and the ankle angle at 90°. The load used in the above-mentioned muscles was 6 kg. The voluntary contraction of the frontalis and masseter was performed by raising the eyebrows and by occluding forcefully respectively. The subject was asked to maintain a steady contraction for the analysis time of the EMG in a shielded room.

Bipolar recording was used for surface EMG. The surface electrode was a silver disc electrode (10 mm in diameter) suspended approximately 2 mm from the skin in a phenol resin retainer (Nihon Kohden Kogyo Co.) which was filled with commercial electrode paste. The skin for the electrode area was scrubbed with ethyl alcohol, and the electrode was fixed to the skin surface above the muscle examined by a disk of double-backed adhesive tape. The active pair were parallel to the muscle fibers usually spaced 30 mm between centers. The ground electrode was placed appropriately in each case. The interelectrode resistance ranged from 10 to 70 KΩ. The EMG signals were amplified by a differential amplifier (Nihon Kohden Kogyo Co., RB-5). The differential input impedance of the amplifier was 10 MΩ, and the frequency response was down less than 3 dB at 3 KHz. The time constant used in this study of the amplifier was 0.1 or 0.3 sec. The output of the amplifier was recorded with a tape recorder (TEAC Co., R-200) and with a polygraph (Nihon Kohden Kogyo Co., RM-85). Tape recording was made in FM at a speed of 15.2 cm/sec. (6 in./sec.) which provided accuracy within the frequency range from dc to 2 KHz.

The digital data processing used in this study required the digitizing of the data, as well as replacing the mathematical operations developed for continuous data with those for discrete data. The EMG data stored on analog magnetic tape were digitized with 10-bit accuracy and the autocorrelation function was calculated using the ATAC 510-20 Medical Data Processing Computer (Nihon Kohden Kogyo Co.) according to the equation

\[ \varphi_i = \varphi(i\Delta\tau) = \sum_{k=-\infty}^{K} f(k\Delta\tau)f(k\Delta\tau - i\Delta\tau), \]

\[ i = 0, 1, 2, \ldots, N - 1 \] (5)

where \( i \) was the lag number, \( N \) was the number of correlation lags, \( \Delta\tau (=NT) \) was the sampling interval and \( K \) was a constant determined by \( N, T \) and the analysis time of data. The analysis time was usually 5 sec. and in some cases 10 sec. The calculated autocorrelation function was punched out in a paper tape.

A raw estimate of the power spectral density function \( P_r \) was defined by (6) at discrete frequencies, since the power spectral density function is an even function of \( f \).

\[ P_r = P(r\Delta f) = \frac{1}{2} \varphi_0 + \sum_{i=1}^{N-1} \varphi_i \cos\left( \frac{\pi ri}{N-1} \right), \]

\[ r = 0, 1, 2, \ldots, N-1 \] (6)
where
\[
\eta = \frac{1}{2(N-1)} dr
\]
and \(r\) was the harmonic number.

Since the lag time had finite length, Hamming window was used to get the smooth estimate of the power spectral density function (PSDF). This window is represented by
\[
P_rH = 0.23P_{r-1} + 0.54P_r + 0.23P_{r+1}, \quad r=1,2,\ldots,N-2
\]
(8)
To eliminate the effect of dc level, the PSDF from \(P_2H\) to \(P_{N-1}H\) was available. The PSDF was calculated using a digital computer.

The resolution and frequency range of the PSDF were somewhat limited by the digital processing of the EMG data used in this study. Usually \(N=64\) and \(dr=2.56\) msec. were used, and the PSDF for the frequency range from 6.2 to 192.2 Hz in steps of 3.1 Hz was obtained. In some cases the PSDF was obtained for the frequency range from 25.2 to 378.0 Hz in steps of 12.6 Hz using \(N=32\) and \(dr=1.28\) msec.

In some cases the frequency spectra of the EMG data stored on magnetic tape were obtained by a modified EEG automatic frequency analyzer (Nihon Kohden Kogyo Co.). Frequency ranges of its ten band pass filters were A : 2-4, B : 4-8, C : 8-13, D : 13-20, E : 20-32, F : 32-64, G : 64-128, H : 128-256, I : 256-512 and J : 512-1024 Hz respectively. Their frequency characteristics are shown in Fig. 1. The analysis time was 5 sec.

RESULTS

For comparison of the PSDF of the EMG, the relative power density (RPD) was calculated by
\[
\text{RPD}(f_r) = \frac{P_rH}{\sum_{r=2}^{N-2} P_jH} \times 100 \%
\]
(9)
KOGI & HAKAMADA (1962a) reported that it was necessary to analyze the EMG for at least a few seconds in order to obtain steady results corresponding to the sustained isometric-isotonic contraction of the muscle. The power spectra of the deltoid and rectus femoris were compared for the analysis time 5 sec. and 10 sec. to investigate the effect of analysis time. Since there was no significant difference between the power spectrum for 5 sec. and that for 10 sec. as shown in Fig. 2, the power spectra for 5 sec. were obtained in all subsequent analyses in order to avoid the effects of fatigue.

In order to compare the frequency spectra obtained by the autocorrelation and its Fourier transformation technique with those obtained by the band pass filter technique, the powers corresponding to each

*Fig. 1. Frequency characteristics of ten band pass filters of the automatic frequency analyzer.*
Power Spectral Analysis of Surface electromyograms

Fig. 2. EMG power spectra of the deltoid for 5 sec. and 10 sec.

Fig. 3. EMG frequency spectra of the biceps brachii obtained by the autocorrelation and its Fourier transformation technique and by the band pass filter technique.

Fig. 4. EMG power spectrum of the masseter obtained for the frequency range from 25.2 to 378.0 Hz in steps of 12.6 Hz showed rather smooth spectrum as compared with that for from 6.2 to 192.2 Hz in steps of 3.1 Hz.

The frequency components below 10 Hz were thought to be sensitive to small movement artifact during isometric contractions as shown in subject D in Fig. 5. The EMG of some muscles, particularly the pectoralis major, contained sometimes the electrocardiogram (ECG). Since the frequency components around 15 Hz were dominant in the power spectrum of the ECG (Fig. 6), these frequency components in the EMG of the pectoralis major seemed to be caused by the ECG (subject D and Y in Fig. 6).

The variation of the power spectra of the EMG of the biceps brachii with respect to different subjects are illustrated in Fig. 7 which shows four power spectra out of seven subjects. Although there were some variations among subjects, the dominant frequency range of the biceps brachii was from 10 to 110 Hz in all
The typical power spectra of various muscles are shown in Fig. 4~Fig. 7 and Fig. 9~Fig. 14. It was evident that there existed different ranges of dominant frequency for different muscles. The dominant frequency range was found to be from 10 to 110 Hz for the biceps brachii, triceps brachii, brachioradialis, pectoralis major, vastus medialis and vastus lateralis, while this range was from 10 to 150 Hz for the deltoid and rectus femoris. The tibialis anterior appeared to have an intermediate power spectrum pattern of these two muscle groups. All these muscles had significant energy in the frequency range approximately from 10 to 200 Hz. On the other hand, the EMG power spect-
Fig. 6. EMG power spectra of the pectoralis major and power spectrum of ECG.

Fig. 7. EMG power spectra of the biceps brachii.

Fig. 8. EMG power spectra of the biceps brachii in a single subject (D) on two occasions, 20 February and 15 March.

Fig. 9. EMG power spectra of the triceps brachii.

ra of the gastrocnemius, masseter and frontalis were broadened by the accession of higher frequencies. The energy above 300 Hz was comparatively scanty in the frontalis, while the gastrocnemius and masseter had some energy even above 300 Hz.

In order to elucidate the power spectrum patterns of various muscles, the cumula-
Fig. 10. EMG power spectra of the brachioradialis.

Fig. 11. EMG power spectra of the deltoid.

Fig. 12. EMG power spectra of the rectus femoris and vastus medialis.

Fig. 13. EMG power spectra of the tibialis anterior.
Power Spectral Analysis of Surface electromyograms

Fig. 14. EMG power spectra of the frontalis.

Fig. 15. Cumulative power of the EMG of the biceps brachii, rectus femoris, frontalis and gastrocnemius in a single subject (K).

tive power (CP) was calculated by

\[
CP(f_r) = \frac{\sum_{i=2}^{r} P_i H_i}{\sum_{i=2}^{N} P_i H_i} \times 100 \quad \text{(%)}
\]

\[ r = 2, 3, \ldots, N - 2 \quad (10) \]

Fig. 15 illustrates the CP of typical muscles in a single subject.

DISCUSSION

There are differences with respect to methods of measurement and frequency analysis technique of the EMG data among researchers. Although surface electrodes and subcutaneous electrodes have the advantages of their own, surface elec-
trodes seem to be advantageous to detect the overall activity of the muscle in that they are easily applied and not injurious to subject. KOMI & BUSKIRK (1970) reported that the reproducibility of EMG recording with bipolar surface electrodes was much better than with inserted wire electrodes, and that their bipolar surface electrode method was as reproducible as DeVries' (1968) unipolar surface electrode method. In unipolar method some problems arise concerning the site of a reference electrode. Bipolar surface electrode method was used in this study. The interelectrode resistance in this study was higher as compared with those reported previously. But it seems to be no problem because HAYES (1960) reported that there was no apparent relationship between the interelectrode resistance and the level of tissue noise.

Power spectral analysis revealed the effect of small movement artifact in the frequencies below 10 Hz and the effect of the ECG around 15 Hz. NIGHTINGALE (1959) reported similar results with bipolar surface electrodes concerning small movement artifact. The autocorrelation and its Fourier transformation technique yielding power spectrum appears to be useful for the fundamental studies on muscle functions, although there are some limitations in respect to the resolution and frequency range of the power spectrum of the EMG obtainable.

There were some variations in the EMG power spectra of a muscle among subjects. The intra- and inter-individual variations will be discussed in another paper.

Some researchers observed similar EMG frequency spectra for different muscles. FEX & KRAKAU (1958) reported that the frequency maximum recorded by surface electrodes was within the same range for different muscles (the tibialis anterior, gastrocnemius, quadriceps femoris, biceps brachii and brachioradialis), and that the maximum for the frequency band of the needle electrodes either lay within the frequency band of the simultaneous surface electrodes or constituted a subharmonic to this band. HAYES (1960) found similar EMG frequency spectra for different bipolar surface electrode sites (the biceps, forearm, lips, masseter and frontalis) by the band pass filter technique and reported that the frequencies above 200 Hz contributed little to the total voltage. SCOTT (1967) reported that the gross myo-electric signals, measured with subcutaneous wire electrodes and analyzed by the autocorrelation and its Fourier transformation technique, had significant energy only in the frequency range approximately from 30 to 200 Hz for the biceps brachii, flexor carpi radialis, internal oblique and rectus femoris.

Contrary to these results, a number of researchers reported that there existed different ranges of dominant frequency for different muscles. WALTON (1952) reported that frequency analysis of the EMG using needle electrodes and band pass filter technique revealed a peak frequency response at 100-200 Hz in all the large limb muscles (the deltoid, pectoralis major, biceps brachii, brachioradialis, gluteus maximus, quadriceps femoris, gastro-
Power Spectral Analysis of Surface electromyograms

cnemius and tibialis anterior) and at 200-250 Hz in facial muscles (the masseter and orbicularis oris) and small muscles of the hand (the flexor pollicis brevis and adductor pollicis). Kogi & Hakamada (1962a) reported that the dominant frequencies determined by Fourier analysis of the bipolar surface EMG for 0.24 sec. were 50-60 Hz in the sternocleidomastoidus, biceps brachii, brachioradialis and tibialis anterior, 50-80 Hz in the triceps brachii, trapezius, extensor digitorum, extensor carpi radialis and flexor carpi ulnaris, and 100-200 Hz in the masseter and gastrocnemius. Kaiser & Petersen (1963) reported from the study with needle electrodes by the band pass filter technique that peak activity of the orbicularis oris was around and above 200 Hz while the biceps brachii and tibialis anterior showed an activity with maximum below 200 Hz. Sato (1964) reported that such tendency as lower frequency dominance of the bipolar surface EMG from the biceps brachii and higher frequency dominance of that from the gastrocnemius was observed, although it was difficult to determine the dominant frequencies of each muscle because of the wide range of the frequency spectra under various conditions. Kikuchi (1968) reported that the flexor digitorum superficialis, biceps brachii, tibialis anterior, gastrocnemius and rectus femoris had the nearly constant distributions of frequency spectra of the bipolar surface EMG respectively. Chaffin (1969) concluded from the study for the biceps brachii, deep finger flexors, triceps brachii, vastus medialis and rectus femoris with unipolar surface electrodes by the band pass filter technique that separate “norm” for the frequency spectra would most likely have to be derived for each muscle or muscle group. Kwatny et al (1970) observed the difference of the power spectra between the extensor digitorum and flexor pollicis brevis with the unipolar surface electrodes by the autocorrelation and its Fourier transformation technique. The results in this study confirm the view that there exist different ranges of dominant frequency of the EMG for different muscles. The significant energy of the EMG was within a frequency range from 10 to 200 Hz in the biceps brachii, triceps brachii, brachioradialis, pectoralis major, vastus medialis and lateralis, tibialis anterior, deltoid and rectus femoris, although there were some variations in the power spectra among these muscles. On the other hand, the power spectra of the gastrocnemius, masseter and frontalis were broadened and they had also significant energy above 200 Hz. The differences in results in this study from those reported by other researchers who tested the same muscles may be explained on the basis of differences in methods of measurement and frequency analysis technique of data.

Richter (1928) maintained that the frequency at which the large waves from the muscle with unipolar surface electrodes came into phase seemed to depend on the length of the reflex arc. The shorter the arc the higher the frequency. Thus the frequencies were near 100 Hz in the masseter, 70-80 Hz in the biceps brachii, 60 Hz in the forearm and 40 Hz in the
tibialis anticus. But it is hardly probable from this study to explain the differences of the EMG power spectra of different muscles by the length of reflex arc.

It is well known that the skeletal muscles of the higher vertebrates are of two kinds, namely tonic red muscle and phasic white muscle, and that most of man's striated muscles contain both types of muscle fibers but differing proportions. Tokizane & Shimazu (1964) showed the functional differentiation of human skeletal muscles, having compared the EMG pattern of motor units for various muscles. It seems apparent from the studies cited here that the EMG frequency spectra of the facial muscles, the small muscles of the hand and the gastrocnemius show higher frequency dominance. The EMG frequency spectra of the facial muscles and the small muscles of the hand may suggest the relationship between the EMG and phasic characteristics of these muscles. This wouldn't, however, explain the EMG of the gastrocnemius. The power spectra of the EMG may depend on many factors such as the number of active motor units, their innervation ratio, the discharge frequencies and the degree of synchronization of motor unit discharges. Further work is required to determine the relative importance of these factors.

It was noticed that some subject had a characteristic power spectrum pattern. This is shown particularly in the power spectra of the biceps brachii and brachioradialis in subject K (Fig. 7 and Fig. 10), whose power spectra were relatively compressed in bandwidth. This subject had been doing karate practice. In this respect further investigation is required.

ACKNOWLEDGMENT

I wish to thank Professor M. Sato, Department of Ergonomics, Kyushu Institute of Design for his encouragement. I also wish to thank the subjects who were students of Kyushu Institute of Design.

This work was supported in part by a grant from Science Foundation, the Ministry of Education in Japan.

REFERENCES


Power Spectral Analysis of Surface electromyograms


表面筋電図のパワースペクトル

佐藤 陽彦
九州芸術工科大学 人間工学教室

8人の被験者を用いて種々の筋の等尺性収縮時の双極表面筋電図の自己相関関数をフーリエ変換した後、ハミング窓によって補正して、そのパワースペクトルを3.1 Hz 毎に6.1〜192.2 Hz の周波数成分にわたって、また一部については12.6 Hz 毎に25.2〜378.0 Hz の周波数成分にわたって求めた。

小さな動きによる影響は10 Hz 以下の周波数成分に、心電図の影響は約15 Hz の周波数成分に現われる。表面筋電図のパワースペクトルは筋によって異なり、同一筋においても被験者によってかなりの相違がみられる。しかし一般に、上腕二頭筋、上腕三頭筋、腕検筋、大脛筋、内側広筋、外側広筋、前腕骨筋、三角筋、大腿直筋の筋電図では10〜200 Hz の周波数成分が優勢であり、腸筋、前頭筋、咬筋では200 Hz 以上の成分もかなり存在する。