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Departments of Clinical Neurophysiology and Orthopaedic Surgery,
Sahlgrenska Sjukhuset, University of Göteborg,
the Division of Applied Electronics, Chalmers University of Technology,
Göteborg, Sweden,
and the Kaiser Laboratory, Copenhagen, Denmark.

POWER SPECTRA OF MYOELECTRIC SIGNALS IN MUSCLES OF ARM AMPUTEES AND HEALTHY NORMAL CONTROLS

P. HERBERTS, E. KAISER, R. MAGNUSSON & I. PETERSÉN

In recent years, the method of controlling externally powered prostheses by means of myoelectric signals has received increasing attention. Systems employing this method have been successfully designed and tested. It is generally agreed, however, that the design of an optimum system requires an extended knowledge of the properties of the myoelectric signal.

In most investigations of these signals, considerable attention has been paid to the characteristics, primarily the duration, of individual muscle action potentials. Action potential interference, however, limits the application of duration measurements to weak muscle contractions only.

In order to characterize the myoelectric signal at moderate and strong muscle contractions other methods must be used. One such method is the measurement of the signal power spectrum. Spectrum measurements have been reported by Richardsson (1951), Walton (1952), Krakau (1956), Fex & Krakau (1958), Hayes (1960), Becker (1960), Kogi & Hakamada (1962), Kaiser & Petersén 1963 and 1965), Sato (1965 and 1966), and Kopéc & Hausman-Petrusewics (1966). A survey of the methods employed is contained in a paper by Kadefors et al. (1968).

Information on the shape and variation of the myoelectric signal

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power spectrum for muscles in healthy and normal individuals has been limited or nonexistent. Normal values obtained with the method used in the present paper, for instance, have been stated for the biceps brachii and orbicularis oris muscles only (Kaiser & Petersén 1965). Values for the muscles of amputees—in the stump region or elsewhere—have only been discussed briefly (Petersén 1966).

The purpose of the present investigation is to obtain detailed information on the power spectra of myoelectric signals from different muscles of arm amputees and controls. In our opinion such an investigation is essential for a proper evaluation of the applicability of myoelectric signals to prosthesis control.

MATERIAL

The power spectrum investigations were carried out for a series of 50 uninjured males as well as for a series of 30 male arm amputees, all aged between 20 and 50 years. The controls had not been subjected to neurological lesions or diseases, or severe accidents. In the control series the following muscles were examined: mm. trapezius, deltoideus, biceps brachii, brachioradialis, extensor digitorum communis, interosseus dorsalis I manus, vastus lateralis, tibialis anterior, soleus, gastrocnemius, and extensor digitorum brevis.

The series of arm amputees consisted of 30 males who had been operated upon during the period 1934–1966. Only patients amputated above and below the elbow were studied. Thus, no cases of exarticulations in the wrist, elbow joint or shoulder joint were included. The series comprised 7 patients amputated above the elbow and 23 patients amputated below the elbow. The majority of the patients had been amputated at ages ranging from 11 to 30 years. The amputations were performed 1 to 33 years—in 50 per cent of the cases 10 to 20 years—before the power spectrum investigations. Traumatic lesion was the cause of amputation in 27 cases, tumour in 2 cases and infection in 1 case. 17 of the patients had lost their left arm and hand and 13 their right. The following muscles of the forearm amputees were studied: mm. biceps brachii and brachioradialis, stump muscles on the extensor side of the forearm, and stump muscles on the flexor side of the forearm. Muscles studied on the above-elbow amputees were remaining stump muscles corresponding to mm. biceps brachii, triceps brachii, deltoideus and trapezius. Due to the great anatomical varia-

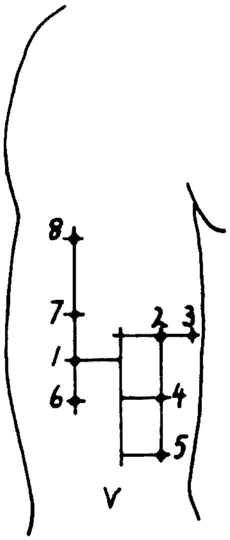

Figure 1. Needle electrode positions in m. biceps brachii of controls.

tions in arm amputees it was not possible to investigate all these muscles in all cases. Among the forearm amputees, all four muscles could be investigated in 18 cases only, and among the above-elbow amputees in two cases only. The number of m. triceps brachii measurements was not sufficient for statistical analysis.

The myoelectric signals of the 50 uninjured controls displayed no abnormalities as judged by standard clinical electromyography.

Among the amputees, EMG signs of lower motoneuron lesion were found for a total of 27 muscles. In most cases EMG signs of these lesions were moderate, single action potentials during maximum voluntary contraction appearing only exceptionally. Spontaneous activity such as fibrillary action potentials or a certain type of positive potentials were observed in altogether four muscles of two patients. For one muscle the EMG pattern showed signs of either a myopathy or a reinnervation of the muscle. This patient had been amputated on account of gangrene caused by septic embolus.

For 122 muscles the EMG was classified as “normal”. In nine of these muscles, however, polyphasic potentials amounted to 10–20 per cent as compared to the considerably lower percentages stated as normal for limb muscles (Petersén & Kugelberg 1949, Buchthal & Rosenfalck 1955, Buchthal 1960). Furthermore, seven muscles yielded an

EMG picture characterized by unusually smooth action potentials of—as estimated by inspection only—slightly increased duration (cf. Petersén 1966).

METHODS

The myoelectric signals were picked up by means of coaxial needle electrodes having an external diameter of 0.65 mm (DISA Elektronik, type 13 K 03). The needle electrodes were inserted essentially perpendicular to the direction of the muscle fibres, with the tip of the needle at a depth of 0.5 to 1 cm in the muscle.

In the case of uninjured controls, signals from eight positions of the needle in nine muscles of the right-hand side extremities were analyzed. The muscles investigated were mm. trapezius, deltoideus, biceps brachii, brachioradialis, extensor digitorum communis, vastus lateralis, tibialis anterior, soleus and gastrocnemius. The positions of the needle in the biceps brachii muscle, shown in Figure 1, were carefully defined in accordance with a procedure developed by Kaiser & Petersén (1965). In this method the end-plate zone of the muscle is located with the aid of electric stimulation, by finding the point having the lowest threshold of stimulation. Point 1 is situated in the end-plate zone of the long head of the biceps, 1.5 mm from the medial edge of the muscle. Point 3 is the point having the lowest threshold of stimulation in the short head of the biceps. Through this point a transversal line is drawn, on which point 2 is situated 1.5 cm medially to the lateral edge of the short head. Point 5 is located in the most distal part of the short head on the same longitudinal line as point 2. Point 4 is situated halfway between points 2 and 5. Points 6 and 7 are 1.5 cm distal and 1.5 cm proximal, respectively, to point 1. Point 8 is located as proximally as possible in the long head of the biceps.

Needle positions in the other muscles were not defined with this great accuracy. Still, the needles were placed according to a consistent plan, *viz.* in two parallel rows of extensions and mutual distances adapted to the particular muscles. Kaiser & Petersén (1965) have investigated the relative magnitudes of myoelectric signal power in octave bands centered at 50, 200 and 800 Hz for the biceps brachii and orbicularis oris muscles. The observations reported in the present paper include the octave centered at 1600 Hz also. In addition to the nine muscles mentioned above, five other muscles were investigated. In 25 controls, mm. biceps brachii, brachioradialis and extensor digitorum communis of the left side were examined. In all 50 controls,

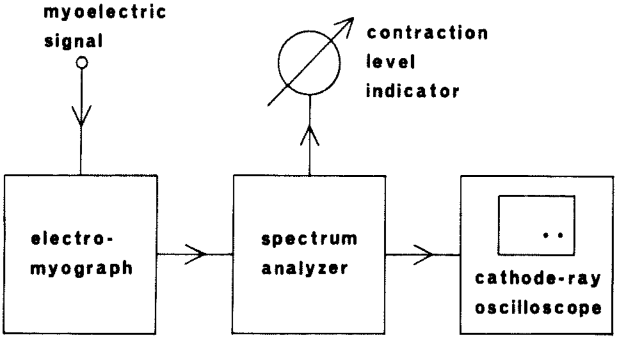

Figure 2. Block diagram of power spectrum measurement.

four measurements were taken from the left side and four measurements from the right side of mm. interosseus dorsalis I manus and extensor digitorum brevis. Needle positions in the latter two muscles were not selected to form any particular pattern.

In the case of arm amputees, myoelectric signals from each muscle investigated were analyzed for four needle positions only, as the stump region frequently is sensitive to pain and trauma. Due to anatomical variations between the arm amputees, the needle positions could not be standardized. The depth of insertion varied with the size of the remaining muscle, from 0.5 to 2.0 cm.

In the case of uninjured controls, the temperature of the right biceps brachii muscle was measured in the vicinity of point 1. For 20 of the controls, the muscle temperature was measured in the vicinity of points 1 and 8 on the right side and of point 1 on the left side. Muscle temperature of the arm amputees was measured in the extensor muscles of the forearm. The temperature measurements were performed by means of a needle-type thermoelement instrument (ELLAB, type TE3, outer diameter of needle 0.7 mm).

The power spectra were measured by means of a method and an instrument described by Kaiser & Petersén (1963, 1965). The method is based on passing the myoelectric signal through four octave band-pass filters centered at 50 Hz, 200 Hz, 800 Hz, and 1600 Hz, respectively. The four filter outputs are rectified, and the resulting DC voltages are presented using the voltage from the 200 Hz filter as a reference. The three ratios thus obtained—power in the 200 Hz octave over power in the 50 Hz octave, power in the 200 Hz octave over power in the

800 Hz octave, and power in the 200 Hz octave over power in the 1600 Hz octave—provide a measure of the *shape* of the power spectrum.

A block diagram of the experimental set-up is shown in Figure 2. The muscle action potentials are first amplified in a DISA electromyograph, the output of which is fed to a specially designed spectrum analyzer. The amplification of the electromyograph was constant throughout the investigation, and was adjusted to a value corresponding to a film-recorder deflection sensitivity of 50 μV/mm. The high-pass filter time constant of the instrument was 1 second. The spectrum analyzer contains a voltmeter measuring the r.m.s. value of the unfiltered muscle signal, and thus serving as a contraction level indicator.

The spectrum analyzer also contains the four octave band-pass filters and rectifiers mentioned above. By means of a logarithmic amplifier and a switching system the four rectified signals are converted into three output voltages proportional to the ratios, in dB, of the power in the octave centered at 200 Hz to the powers in the octave centered at 50, 800 and 1600 Hz, respectively.

The output voltages are presented as the positions of two bright spots, the octave loci, on the screen of a cathode-ray oscilloscope (Tektronix, type 502). The horizontal deflections of the two spots are proportional to the 200 Hz/800 Hz and 200 Hz/1600 Hz activity ratios, respectively. The vertical deflections of both spots are proportional to the 200 Hz/50 Hz activity ratio. All three deflection sensitivities were 1 mm/dB, with associated over-all time constants of 0.3 seconds.

The three activity ratio voltages were not compensated for the differences in bandwidth of the four octave filters. It follows that the indicated 200 Hz/50 Hz ratio was 6 dB above the true value, the indicated 200 Hz/800 Hz ratio was 6 dB below the true value, and the indicated 200 Hz/1600 Hz ratio was 9 dB below the true value. We use the following notation for the various ratios:

a = *indicated* ratio, in dB, of the activity (r.m.s. value) in the reference octave centered at 200 Hz ("the 200 Hz band") to the activity in the octave centered at 50 Hz ("the 50 Hz band"),
b = *indicated* ratio of the activity in the 200 Hz band to the activity in the 800 Hz band,
c = *indicated* ratio of the activity in the 200 Hz band to the activity in the 1600 Hz band,
α = a—6 = *true* ratio of the activity in the 200 Hz band to the activity in the 50 Hz band,

$\beta = b + 6 =$ *true* ratio of the activity in the 200 Hz band to the activity in the 800 Hz band, and

$\gamma = c + 9 =$ *true* ratio of the activity in the 200 Hz band to the activity in the 1600 Hz band.

For calibration of the spectrum analyzer we used four generators supplying sinusoidal signals of frequencies 50, 200, 800 and 1600 Hz, respectively. Each generator was fitted with an attenuator calibrated in dB. Signals of the same amplitude (all ratios 0 dB) were simultaneously fed to the spectrum analyzer from the four generators, and the cathode-ray spot was adjusted to coincide with the screen's zero point. The 50 Hz, 800 Hz and 1600 Hz signals were then attenuated 10 dB, and the oscilloscope gains were adjusted to produce coordinate changes of 10 mm on the cathode-ray tube screen. The coordinates obtained were independent of the absolute value of the voltages provided the latter were within the 50 dB linear range of the filter rectifier circuits. The performance of the spectrum analyzer was also checked for input signals consisting of filtered and unfiltered Gaussian noise.

The degree of muscle contraction was standardized with the aid of the contraction level indicator mentioned above. The subjects were instructed to maintain, for a few seconds, the (moderate) contraction intensity yielding a specified voltmeter deflection. During this period, the locus coordinates were read—by the same person throughout the entire test series—from the screen of the oscilloscope.

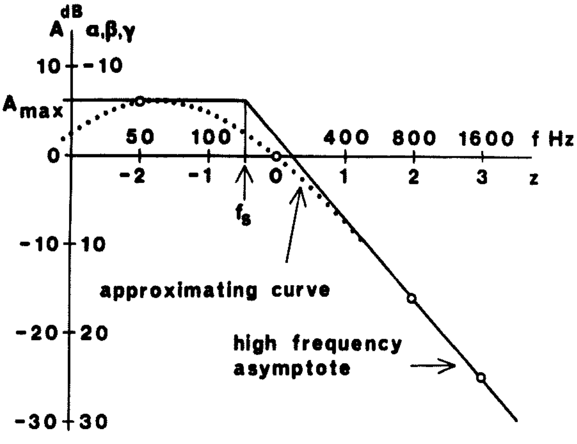

Figure 3. Piece-wise linear model of power spectrum ($\alpha = -6$ dB, $\beta = 16$ dB, $\gamma = 25$ dB).

A detailed analysis of the measurement procedure (Kaiser et al., to be published) indicates that the over-all systematic error of the power spectrum values obtained is less than 1 dB. The random error component has a standard deviation of about 0.5 to 0.7 dB.

The three ratios α, β and γ define three points in the power *vs* frequency diagram shown in Figure 3. The fourth point shown in the diagram, at 200 Hz and 0 dB, is the reference point. The average power spectrum of myoelectric signals from a particular muscle passes through these four points. In order to give a simple piece-wise linear description of the shape of the power spectrum we have employed the following procedure.

A straight line, the high frequency asymptote, is passed through the two points at 800 and 1600 Hz. The slope of this line, s dB/octave, is the difference between the two ratios β and γ. The three points at 50, 200 and 800 Hz are connected with the curve

$$A = A_1 z + A_2 z^2 + A_3 z^3 \qquad (1)$$

where the independent variable z is normalized logarithmic frequency,

$$z = {}^{2}\log f(\mathrm{Hz})/200 \qquad (2)$$

and the coefficients A_i are chosen in such a way that the curve has the same slope as the high-frequency asymptote at 800 Hz:

$$A_1 = (\alpha - 9\beta + 4\gamma)/8 \qquad (3\,a)$$

$$A_2 = -(\alpha + \beta)/8 \qquad (3\,b)$$

$$A_3 = (\alpha + 7\beta - 4\gamma)/32 \qquad (3\,c)$$

The corner frequency f_s is defined by the intersection of the maximum level $A_{\max}$ of curve (1) and the high-frequency asymptote. The values of $A_{\max}$ and f_s are as follows:

$$A_{\max} = A_1 z_{\max} + A_2 z^2_{\max} + A_3 z^3_{\max} \qquad (4)$$

where

$$z_{\max} = -(A_2 + \sqrt{A_2^2 - 3A_1A_3})/3A_3 \qquad (5)$$

(provided that $A_2^2 > 3A_1A_3$ and $A_3 \# 0$),

and

$$f_s = 200 \cdot 2^{z_s} \qquad (6)$$

where

$$z_s = 2 - (\beta + A_{\max})/(\gamma - \beta) \qquad (7)$$

The statistical analysis involved two types of comparison, *viz.* the comparison of several means and the comparison of a single mean with a hypothetical value or a difference between two means.

The former comparisons were performed by analyses of variance employing a hierarchical model with two levels. Individuals were considered as primary groups, muscles as secondary groups, and the separate measurements as replicates. "Individuals" were assumed to be a random effect and "muscles" a systematic effect. This means that "individuals" were regarded as a sample from a very great population, whereas "muscles" in the sample were the particular muscles in which we were interested in the present investigation.

This method was employed both for the uninjured controls and for the amputees in analyzing the difference between muscle means, and also in analyzing means referring to the right and left side (in this case "sides" formed the secondary groups).

When these tests resulted in significant main effects, contrasts were analyzed by Tukey's T-method. In all other cases, in which only one mean or the difference between two means was to be analyzed, the normal test was employed.

Throughout this study, a 5 per cent level of significance has been used in the statistical tests.

RESULTS

Uninjured Controls

Muscles of the Right Arm and Leg

The mean values and standard deviations of the three ratios α, β and γ, as well of the spectrum parameters s, f_s and $A_{\max}$, of nine muscles of the right arm and leg are shown in Table 1. The table also shows the correlation coefficients $r_{\alpha\beta}$, $r_{\alpha\gamma}$ and $r_{\beta\gamma}$ between spectrum levels at 50, 800 and 1600 Hz.

Differences between the six parameter values obtained for different individuals and different muscles were evaluated with the aid of six two-way analyses of variance using hierarchical models. The analyses show that statistically significant differences exist between the mean values of individuals as well as of muscles. This result holds for all six parameters.

The analyses of variance also yield the standard deviation components shown in Table 2. As can be seen from the table, the most im-

Table 1. Power spectrum characteristics of the myoelectric signal for moderate controls aged

Muscle	α(dB) mean	α(dB) std dev.	β(dB) mean	β(dB) std dev.	γ(dB) mean	γ(dB) std dev.
Trapezius	—6.6	2.6	16.6	2.5	25.9	4.1
Deltoideus	—5.9	3.0	16.1	1.9	24.5	4.1
Biceps brachii	—5.7	2.4	16.3	2.0	26.4	4.0
Brachioradialis	—6.0	2.6	16.2	1.7	25.0	4.4
Extensor digitorum communis	—5.8	3.1	16.2	2.0	24.7	5.4
Vastus lateralis	—5.0	2.6	16.0	1.7	25.0	3.7
Tibialis anterior	—6.3	2.6	16.3	2.3	26.4	3.8
Soleus	—4.3	2.9	16.5	2.3	26.2	3.8
Gastrocnemius	—5.5	2.9	17.3	2.7	27.3	4.2

Parameters α, β and γ are ratios of activity power in a band centered at 200 Hz to activity powers in equally wide bands centered at 50, 800 and 1600 Hz, respectively. Parameters s, f_s and $A_{\max}$ are slope of high-frequency asymptote, corner frequency, and difference between low-frequency and 200 Hz levels of corner fre-

portant source of variation for all six parameters is to be found within the muscle, i. e. in the differences between values obtained for different positions of the needle electrode *within a muscle.* The next most important source of variation, also for all six parameters, is the differences *between muscles.* It follows that the least important factor—again for all six parameters—is *interindividual* variation. The standard deviations of the set of parameters α, β, γ consistently take on their largest values for parameter γ and their smallest values for parameter β. Since parameters s, f_s and $A_{\max}$ are of different dimensions, their deviations cannot immediately be compared. It is evident, however, that the corner frequency f_s — not surprisingly—has considerable variation.

The fact that interindividual variations are significant implies that individuals having high parameter values for one muscle have high parameter values for other muscles also.

Tables 3–8 show matrices of the differences between the six parameter values, respectively, of the nine different muscles. By means of the T-method for comparisons of contrasts (Brownlee 1960) it is found that pair differences having magnitude exceeding 0.5 for α, 0.4 for β, 0.8 for γ, 0.6 for s, 16 for f_s, and 0.9 for $A_{\max}$ are significant. These differences are printed in italics.

contractions of nine muscles of the right arm and leg in 50 uninjured male 20 to 50 years.

s(dB/octave)		f_s (Hz)		$A_{\max}$ (dB)		$r_{\alpha,\beta}$ (50/800)	$r_{\alpha,\gamma}$ (50/1600)	$r_{\beta,\gamma}$ (800/1600)
mean	std dev.	mean	std dev.	mean	std dev.			
—9.2	3.0	129	77	8.0	3.9	0.10	—0.07	0.73
—8.4	3.1	114	75	7.8	5.5	—0.01	—0.02	0.70
—10.2	3.1	166	82	6.9	3.9	—0.05	—0.08	0.68
—8.7	3.0	126	75	7.4	4.1	0.05	—0.10	0.69
—8.5	3.3	119	82	7.4	3.4	—0.12	—0.20	0.72
—9.0	2.8	115	83	6.4	3.2	0.05	—0.09	0.69
—10.2	2.5	159	70	8.0	5.7	0.15	—0.02	0.76
—9.7	2.6	165	75	5.8	3.0	—0.06	—0.17	0.75
—10.0	2.7	151	80	7.0	3.2	0.02	—0.07	0.78

quency model, respectively. Symbol $r_{\alpha,\beta}$ denotes coefficient of correlation between α and β, etc. Measurements were carried out at eight different needle electrode positions in each muscle.

Several striking features are found in Tables 3–8. Comparison of the number of significant differences for the various parameters shows that, except for m. gastrocnemius, the values of the ratio β are particularly uniform. It is also seen that in a majority of cases significant γ differences are accompanied by significant differences in $s = \beta - \gamma$, occasionally in conjunction with significant differences in one or several of the other parameters also. Significant γ differences accompanied by significant β differences *but not* by significant s differences are quite exceptional (m. gastrocnemius vs. mm. biceps brachii,

Table 2. Partition of total standard deviations (σ of α, β, γ, s, f_s and $A_{\max}$ in contributions due to intramuscular variations (σ_1), intermuscular variations (σ_2), and interindividual variations (σ_3); nine right-side muscles of 50 uninjured controls.

Standard deviation component	α(dB)	β(dB)	γ(dB)	s(dB/octave)	f_s(Hz)	$A_{\max}$ (dB)
σ_1	2.4	1.7	3.5	2.6	71	3.9
σ_2	1.4	1.1	1.8	1.2	32	1.3
σ_3	0.8	0.7	1.3	0.9	21	0.8
σ	2.9	2.2	4.2	3.0	81	4.2

Table 3. Differences, in dB, between average α values of nine muscles (limit of significance = 0.5; significant differences are printed in italics).

	Mean	Trapezius	Deltoideus	Biceps brachii	Brachioradialis	Extens ordigitorum communis	Vastus lateralis	Tibialis anterior	Soleus	Gastrocnemius
Mean		—6.6	—5.9	—5.7	—6.0	—5.8	—5.0	—6.3	—4.3	—5.5
Trapezius	—6.6	—								
Deltoideus	—5.9	*—0.7*								
Biceps brachii	—5.7	*—0.9*	—0.2	—						
Brachioradialis	—6.0	*—0.6*	0.1	0.3	—					
Extensor digitormu communis	—5.8	*—0.8*	—0.1	0.1	—0.2	—				
Vastus lateralis	—5.0	*—1.6*	*—0.9*	*—0.7*	*—1.0*	*—0.8*	—			
Tibialis anterior	—6.3	—0.3	0.4	*0.6*	0.3	0.5	*—1.3*	—		
Soleus	—4.3	*—2.3*	*—1.6*	*—1.4*	*—1.7*	*—1.5*	*—0.7*	*—2.0*	—	
Gastrocnemius	—5.5	*—1.1*	—0.4	—0.2	—0.5	0.3	—0.5	*0.8*	*1.2*	—

Table 4. Differences, in dB, between average β values of muscles (limit of significance = 0.4; significant differences are printed in italics).

	Mean	Trapezius	Deltoideus	Biceps brachii	Brachioradialis	Extens ordigitorum communis	Vastus lateralis	Tibialis anterior	Soleus	Gastrocnemius
Mean		16.6	16.1	16.3	16.2	16.0	16.3	16.5	17.3	
Trapezius	16.6	—								
Deltoideus	16.1	*0.5*	—							
Biceps brachii	16.3	0.3	—0.2	—						
Brachioradialis	16.2	0.4	—0.1	0.1	—					
Extensor digitormu communis	16.2	0.4	—0.1	0.1	0.0	—				
Vastus lateralis	16.0	*0.6*	0.1	0.3	0.2	0.2	—			
Tibialis anterior	16.3	0.3	—0.2	0.0	—0.1	—0.1	—0.3	—		
Soleus	16.5	0.1	—0.4	—0.2	—0.3	—0.3	*—0.5*	—0.2	—	
Gastrocnemius	17.3	*—0.7*	*—1.2*	*—1.0*	*—1.1*	*—1.1*	*—1.3*	*—1.0*	*—0.8*	—

Table 5. Differences, in dB, between average γ values of nine muscles (limit of significance = 0.8; significant differences are printed in italics).

	Mean	Trapezius	Deltoideus	Biceps brachii	Brachioradialis	Extens ordigitorum communis	Vastus lateralis	Tibialis anterior	Soleus	Gastrocnemius
Mean		25.9	24.5	26.4	25.0	24.7	25.0	26.4	26.2	27.3
Trapezius	25.9	—								
Deltoideus	24.5	*1.4*	—							
Biceps brachii	26.4	—0.5	*—1.9*	—						
Brachioradialis	25.0	*0.9*	—0.5	*1.4*	—					
Extensor digitormu communis	24.7	*1.2*	—0.2	*1.7*	0.3	—				
Vastus lateralis	25.0	*0.9*	—0.5	*1.4*	*0*	—0.3	—			
Tibialis anterior	26.4	—0.5	*—1.9*	0	*—1.4*	*—1.7*	*—1.4*	—		
Soleus	26.2	—0.3	*—1.7*	0.2	*—1.2*	*—1.5*	*—1.2*	0.2	—	
Gastrocnemius	27.3	*—1.4*	*—2.8*	*—0.9*	*—2.3*	*—2.6*	*—2.3*	*—0.9*	*—1.1*	—

Table 6. Differences, in dB/octave, between average s *values of nine muscles (limit of significance = 0.6; significant differences are printed in italics).*

	Mean	Trapezius	Deltoideus	Biceps brachii	Brachioradialis	Extens ordigitorum communis	Vastus lateralis	Tibialis anterior	Soleus	Gastrocnemius
Mean		—9.2	—8.4	—10.2	—8.7	—8.5	—9.0	—10.2	—9.7	—10.0
Trapezius	--9.2	—								
Deltoideus	—8.4	*—0.8*	—							
Biceps brachii	—10.2	*1.0*	*1.8*	—						
Brachioradialis	—8.7	—0.5	0.3	*—1.5*	—					
Extensor digitormu communis	—8.5	*—0.7*	*0.1*	—1.7	—0.2	—				
Vastus lateralis	—9.0	—0.2	0.6	*—1.2*	0.3	0.5	—			
Tibialis anterior	—10.2	*1.0*	*1.8*	0	*1.5*	*1.7*	*1.2*	—		
Soleus	—9.7	0.5	*1.3*	—0.5	*1.0*	*1.2*	*0.7*	—0.5	—	
Gastrocnemius	—10.0	*0.8*	*1.6*	—0.2	*1.3*	*1.5*	*1.0*	—0.2	0.3	—

Table 7. Differences, in Hz, between average f_s values of nine muscles (limit of significance = 16; significant differences are printed in italics).

	Mean	Trapezius	Deltoideus	Biceps brachii	Brachioradialis	Extens ordigitorum communis	Vastus lateralis	Tibialis anterior	Soleus	Gastrocnemius
Mean		129	114	166	126	119	115	159	165	151
Trapezius	129	—								
Deltoideus	114	15	—							
Biceps brachii	166	—*37*	—*52*	—						
Brachioradialis	126	— 3	—12	*40*	—					
Extensor digitormu communis	119	10	— 5	*47*	7	—				
Vastus lateralis	115	14	— 1	*51*	11	4	—			
Tibialis anterior	159	—*30*	—*45*	7	—*33*	—*40*	—*44*	—		
Soleus	165	—*36*	—*51*	1	—*39*	—*46*	—*50*	— 6	—	
Gastrocnemius	151	—*22*	—*37*	15	—*25*	—*32*	—*36*	8	*14*	—

Table 8. Differences, in dB, between average $A_{\max}$ values of nine muscles (limit of significance = 0.9; significant differences are printed in italics).

	Mean	Trapezius	Deltoideus	Biceps brachii	Brachioradialis	Extens ordigitorum communis	Vastus lateralis	Tibialis anterior	Soleus	Gastrocnemius
Mean		8.0	7.8	6.9	7.4	7.4	6.4	8.0	5.8	7.0
Trapezius	8.0	—								
Deltoideus	7.8	0.2	—							
Biceps brachii	6.9	*1.1*	0.9	—						
Brachioradialis	7.4	0.6	0.4	—0.5	—					
Extensor digitormu communis	7.4	0.6	0.4	—0.5	0	—				
Vastus lateralis	6.4	*1.6*	*1.4*	0.5	*1.0*	*1.0*	—			
Tibialis anterior	8.0	0	—0.2	—*1.1*	—0.6	—0.6	—*1.6*	—		
Soleus	5.8	*2.2*	*2.0*	*1.1*	*1.6*	*1.6*	*0.6*	*2.2*	—	
Gastrocnemius	7.0	*1.0*	0.8	—0.1	0.4	0.4	—0.6	*1.0*	—*1.2*	—

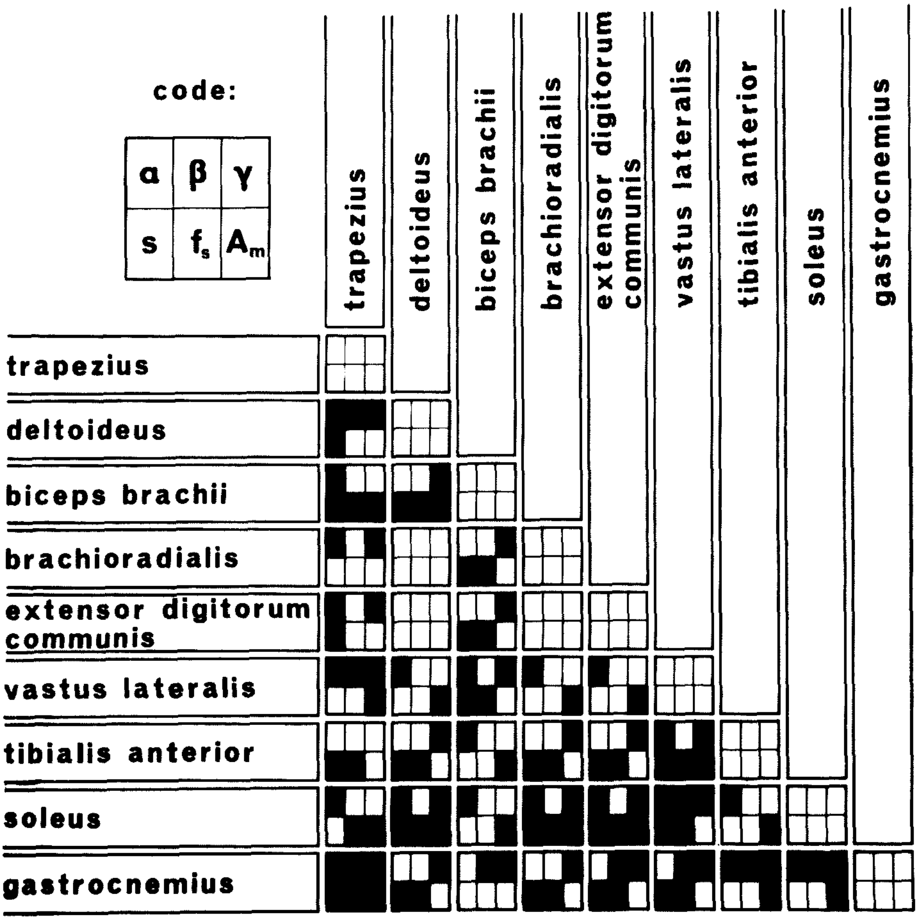

Figure 4. Significant differences (= filled rectangels) between pairs of right-side muscles with respect to α, β, γ, s, f_s and A_{max}.

tibialis anterior and soleus, and m. vastus lateralis vs. m. trapezius).

It should also be noted that the α differences of m. trapezius are significant in all cases but one (higher low-frequency content for m. trapezius) and that the A_{max} differences of m. soleus are significant also in all cases but one (lower low-frequency content for m. soleus, in agreement with the previous statement concerning α).

A simultaneous presentation of all significant differences between pairs of muscles with respect to the six spectrum parameters is given in Figure 4.

The only pairs displaying no statistically significant spectrum parameter differences at all are m. extensor digitorum communis vs. mm. brachioradialis and deltoideus. Nine muscle pairs show significant differences for two parameters only. In six of these cases the differences are displayed by α and $A_{\max}$; this plausible combination is also found in a considerable number of cases having additional parameter differences.

The numbers of statistically significant differences displayed by the individual muscles are more or less evenly distributed between 18 and 31, mm. brachioradialis and deltoideus having the lowest and mm. soleus and gastrocnemius the highest numbers. A similar result is obtained if α, β and γ differences only are considered, or—although less pronouncedly—if s, f_s and $A_{\max}$ differences only are considered.

The only muscle pair for which all six parameter differences are statistically significant is m. gastrocnemius ms. m. trapezius. In five pairs all differences but one are statistically significant. In four of these pairs the nonsignificant difference is contributed by the β parameter.

The detailed investigations on needle position influence, which were carried out for m. biceps brachii, revealed—with two exceptions only—no statistically significant differences between the eight mean α, β, γ, s, f_s and $A_{\max}$ values, respectively. The exceptions were the difference between the mean α values for positions 1 (end-plate region of the long head, $\alpha = -5.2$) and 8 (point most distant from 1, $\alpha = -6.4$), and the mean f_s values for positions 6 (also end-plate region of the long head $f_s = 196$) and 8 ($f_s = 144$). No statistically significant differences at all, however, were found between the average values of the long head and the average values of the short head ($\alpha = -5.7$ for both heads, $f_s = 171$ and 162 for long and short heads, respectively). In comparisons of the right biceps brachii muscle with other muscles we have therefore used averages of all eight long and short head measurements.

Returning to Table 1, a striking feature is the difference in orders of magnitude of the coefficient of correlation $r_{\beta,\gamma}$ (800 Hz vs. 1600 Hz bands) and the coefficients of correlation $r_{\alpha,\beta}$ (50 Hz vs. 800 Hz bands) and $r_{\alpha,\gamma}$ (50 Hz vs. 1600 Hz bands). This difference—large $r_{\beta,\gamma}$ and small $r_{\alpha,\beta}$ and $r_{\alpha,\gamma}$—is universal over the group of muscles, and may be a reflection of the existence of functionally different types of motor units. This might imply that the α value (low-frequency content) is essentially contributed by one type of units, whereas the β and γ values (high-frequency content) are essentially due to another.

Table 9. Power spectrum characteristics of the myoelectric signal for moderate contractions of the left side mm. biceps brachii, brachioradialis and extensor digitorum communis in 25 uninjured male controls aged 20 to 50 years.

Muscle	α(dB)		β(dB)		γ(dB)		s(dB/octave)		f_s (Hz)		$A_{\max}$ (dB)	
	mean	std dev.	mean	std dev.	mean	std dev.	mean	std dev.	mean	std dev.	mean	std dev.
Biceps brachii	—6.8	1.9	17.6	1.5	27.9	3.5	—10.3	2.6	146	61	7.6	2.5
Brachioradialis	—5.7	2.1	17.0	1.1	25.8	3.1	—8.8	2.6	124	65	7.0	5.5
Extensor digitorum communis	—5.8	2.8	16.6	1.2	24.4	3.4	—7.8	2.8	99	65	7.3	2.8

Measurements were carried out at eight different needle electrode positions in each muscle.

Table 10. Partition of total standard deviations (σ of α, β, γ, s, f_s and A_{max} in contributions due to intramuscular variations (σ_1), intermuscular variations (σ_2), and interindividual variations (σ_3); three left-side muscles of 25 uninjured controls.

Standard deviation component	α(dB)	β(dB)	γ(dB)	s(dB/octave)	f_s (Hz)	A_{max} (dB)
σ_1	2.0	1.2	3.0	2.5	60	3.7
σ_2	1.0	0.6	2.1	1.5	31	0.9
σ_3	0.8	0.4	1.0	0.7	15	0.8
σ	2.4	1.4	3.8	3.0	69	3.9

Comparison between Right and Left Side Muscles

1. *Mm. Biceps Brachii, Brachioradialis and Extensor Digitorum Communis:*

The left side mean values and standard deviations of α, β, γ, s, f_s and A_{max} for these three muscles are shown in Table 9.

Analyses of variance were carried out for each of the six spectrum parameters, with the result that statistically significant differences

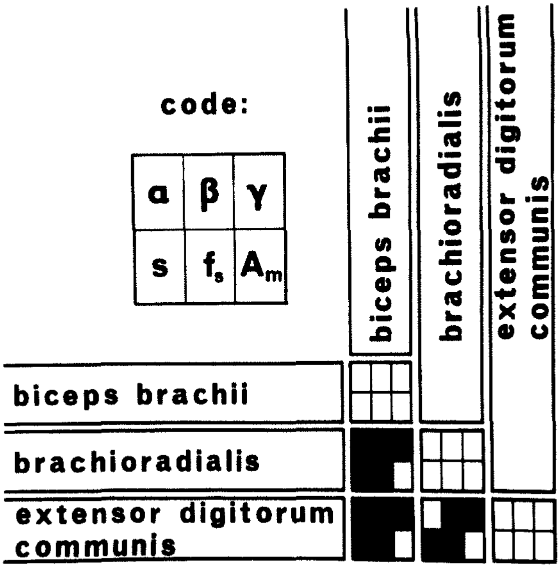

Figure 5. Significant differences (= filled rectangels) between pairs of left-side muscles with respect to α, β, γ, s, f_s and A_{max}.

exist between the mean values of individuals as well as of muscles. This result holds for all six parameters.

The standard deviation components yielded by the analyses of variance are shown in Table 10. As for the right side muscles, intramuscular variation is most important, intermuscular variation is next most important, and interindividual variation is least important. Also as for the right side, the standard deviations of the set of parameters α, β, γ consistently take on their largest values for γ and their smallest values for β.

A simultaneous presentation of all significant differences between pairs of muscles with respect to the six spectrum parameters is given in Figure 5. Comparison of Figures 4 and 5 shows that the number of statistically significant intermuscular differences is larger for the left side than for the right side.

Comparison of the left side values in Table 9 with the corresponding right side values in Table 1 shows the following differences to be statistically significant: α, β, γ, f_s and $A_{\max}$ of m. biceps brachii, β, γ and $A_{\max}$ of m. brachioradialis, and β, s and f_s of m. extensor digitorum communis.

2. *Mm. Interosseus Dorsalis I Manus and Extensor Digitorum Brevis*

The left side and right side mean values and standard deviations of α, β, γ, s, f_s and $A_{\max}$ for each of these two muscles are shown in Table 11.

Differences between individuals and between sides were evaluated by means of two-way hierachical analyses of variance, with the result that differences between individuals are statistically significant for both muscles, whereas statistically significant differences between the right and the left side appear in the α, γ, s, f_s and $A_{\max}$ values only of m. interosseus dorsalis I manus, and in the β and γ values only of m. extensor digitorum brevis. The analyses also yield the standard deviation components shown in Table 12.

The table shows that for these two muscles also, the most important source of variation for all six parameters is to be found within the muscle (cf. Table 2). Interindividual variations are more important than interside variations for all parameters of both muscles except for the s and f_s values of m. interosseus dorsalis I manus.

Comparison of the right side α, β, γ, s. f_s and $A_{\max}$ values in Table 11 with the corresponding values in Table 1 shows, generally speaking,

Table 11. Power spectrum characteristics of the myoelectric signal for moderate m. extensor digitorum brevis in 50

Muscle	Side	α(dB) mean	α(dB) std dev.	β(dB) mean	β(dB) std dev.	γ(dB) mean	γ(dB) std dev.
Interosseus dorsalis I	right	—3.8	3.2	16.3	2.0	27.2	3.9
manus	left	—4.0	3.3	16.6	2.5	26.9	4.6
Extensor digitorum	right	—3.1	3.5	16.6	2.6	27.1	4.6
brevis	left	—2.7	3.0	17.7	3.2	28.7	4.8

Measurements were carried out at four different needle electrode positions in each muscle.

markedly low α and $A_{\max}$ (low-frequency parameters), markedly high γ, s and f_s (high-frequency parameters), and average β. Apart from a moderate increase in magnitude, the right-side coefficients of correlation in Table 11 display the same characteristics as those of the nine right-side muscles in Table 1.

It is interesting to note that statistically significant parameter differences between the left and right sides of mm. interosseus dorsalis I manus and extensor digitorum brevis take place in the same directions as the corresponding statistically significant left to right side differences of mm. biceps brachii, brachioradialis and extensor digitorum communis. This effect is particularly pronounced for parameter β.

Influence of Muscle Temperature

Muscle temperature of the 50 uninjured controls measured in the right-side long head of m. biceps brachii in the vicinity of point 1 varied between 35.0 and 37.5° C; the mean value was 36.4° C. Inspection of scatter diagrams revealed no discernible temperature dependence of the α, β, γ, s, f_s or $A_{\max}$ values. It can be noted that neither does the duration of low-level-contraction action potentials vary significantly over this limited temperature range (see Buchthal et al. 1954).

Temperature differences recorded for 20 uninjured controls between points 1 and 8 of the right side m. biceps brachii and between point 1 of the right side and point 1 of the left side m. biceps brachii did not in any case exceed 0.1° C. Thus, temperature influence cannot explain the power spectrum differences between points 1 and 8 or between the left and right sides.

contractions of the right and left side m. interosseus dorsalis I manus and uninjured male controls aged 20 to 50 years.

s(dB/octave) mean	std dev.	f_s(Hz) mean	std dev.	$A_{\max}$ (dB) mean	std dev.	$r_{\alpha,\beta}$ (50/800)	$r_{\alpha,\gamma}$ (50/1600)	$r_{\beta,\gamma}$ (800/1600)
—10.9	2.9	202	84	5.2	2.9	—0.04	—0.13	0.69
—10.3	3.0	177	79	5.6	2.6	—0.21	—0.35	0.79
—10.5	3.0	190	82	5.0	3.3	—0.18	—0.20	0.81
—11.1	2.9	199	87	4.6	2.5	—0.16	—0.16	0.81

Amputees

The mean values and standard deviations of α, β γ, s, f_s and $A_{\max}$ for muscles of amputees with normal EMG are shown in Table 13. Values obtained for muscles of amputees with neurogenic EMG are shown in Table 14. The tables include the spectrum parameters of those muscle groups only which contain at least three muscles (corresponding to at least 12 myoelectric signals).

Comparison between Muscles Yielding Normal and Neurogenic EMG, Respectively

Due to limited group size, differences between the spectrum parameters of signals from muscles yielding normal and neurogenic EMG

Table 12. Partition of total standard deviations (σ) of α, β, γ, s, f_s and $A_{\max}$ for the two muscles in contributi ons due to intramuscular variations (σ_1), interside variations (σ_2), and interindividual variations (σ_3); 50 uninjured controls.

Muscle	Standard deviation component	α(dB)	β(dB)	γ(dB)	s(dB/ octave)	f_s(Hz)	$A_{\max}$ (dB)
Interosseus	σ_1	2.6	2.0	3.9	2.8	73	2.3
dorsalis I	σ_2	1.4	—	1.3	1.3	33	1.0
manus	σ_3	1.7	1.1	1.4	0.7	31	1.4
	σ	3.4	2.3	4.4	3.1	86	2.9
Extensor	σ_1	2.8	2.3	4.1	2.8	78	2.7
digitorum	σ_2	—	1.1	1.4	—	—	—
brevis	σ_3	1.6	1.6	2.3	1.0	29	1.2
	σ	3.2	4.1	4.9	3.0	83	2.9

Table 13. Power spectrum characteristics of normal myoelectric signals for

Above/below elbow amputation	Muscle	Side	Number of patients	α(dB) mean	std dev.
Above	trapezius	right	3	—6.4	2.7
elbow	deltoideus	left	4	—3.3	3.3
	biceps brachii	right	9	—4.9	3.2
		left	11	—4.9	3.7
Below	brachioradialis	right	7	—3.0	4.3
elbow		left	12	—3.0	2.8
	stump extensor	right	6	—4.5	3.6
		left	8	—1.9	3.6
	stump flexor	right	6	—3.0	3.8
		left	9	—4.7	3.7

Measurements were carried out at four different needle electrode positions in each muscle.

could only be analyzed for the right and the left side, respectively, of the stump extensor muscles and for the right side of the stump flexor muscles. Comparison of the corresponding spectrum parameters of these muscles, shown in Tables 13 and 14, reveals statistically significant differences for all parameters except f_s of the right side flexor muscles. In view of this result, further comparisons within the group of amputees as well as between this group and the group of controls were performed for signals classified as normal only (with one exception).

Table 14. Power spectrum characteristics of neurogenic myoelectric signals for 20 to

Muscle	Side	Number of patients	α(dB) mean	dev. std	β(dB) mean	dev. std
Stump extensor	right	3	0.1	3.5	16.9	1.7
	left	3	—8.7	4.0	20.6	6.0
Stump flexor	right	4	—3.9	2.1	21.0	4.6

Measurements were carried out at four different needle electrode positions in each muscle.

moderate contractions of ten muscles of male amputees aged 20 to 50 years.

β(dB)		γ(dB)		s(dB/octave)		f_s (Hz)		A_{max} (dB)	
mean	std dev.	mean	std dev.	mean	std dev.	mean	std dev.	mean	std dev.
16.4	3.6	27.6	5.3	—11.2	2.2	158	76	12.4	14.6
17.6	2.0	28.4	5.3	—10.8	3.9	184	100	5.0	2.4
15.4	2.1	23.3	3.3	—7.9	2.5	114	64	8.6	9.8
16.4	2.1	25.9	4.1	—9.5	3.0	143	80	7.7	7.3
15.8	2.2	24.6	5.3	—8.8	3.6	144	96	7.3	10.0
16.3	2.4	25.9	5.0	—9.6	3.6	169	94	4.9	0.9
16.0	1.0	26.0	3.2	—10.0	2.9	167	64	6.3	3.0
15.7	1.7	25.1	3.4	—9.4	3.0	248	24	5.6	1.6
16.4	2.4	26.3	4.2	—9.9	3.3	171	83	3.8	3.9
15.9	2.4	26.8	2.9	—10.9	2.9	204	81	6.0	3.5

Comparison between Muscles Yielding Normal EMG

Differences between the six parameter values obtained for different individuals and different muscles having normal EMG were evaluated with the aid of analyses of variance using hierarchical models. These investigations were carried out for mm. biceps brachii and brachioradialis, and the stump extensor muscle of below-elbow amputees. Right side muscles (for amputees) and left side muscles (eight amputees) were analyzed separately.

The analyses show statistically significant differences between the mean values of muscles for all parameters except A_{max} of the left

moderate contractions of three muscles of male below-elbow amputees aged 50 years.

γ(dB)		s(dB/octave)		f_s (Hz)		A_{max} (dB)	
mean	dev. std	mean	dev. std	mean	dev. std	mean	dev. std
28.6	3.8	—11.7	2.4	243	56	2.9	1.3
31.6	3.8	—11.0	3.4	157	103	9.6	4.9
32.8	3.9	—11.8	2.0	178	90	6.0	2.4

Table 15. Partition of total standard deviations (σ) of α, β, γ, s, f_s and $A_{\max}$ in contributions due to intramuscular variations (σ_1), intermuscular variations (σ_2), and interindividual variations (σ_3); four right-side amputees and eight left-side amputees.

Muscles	Standard deviation component	α(dB)	β(dB)	γ(dB)	s(dB/octave)	f_s(Hz)	$A_{\max}$ (dB)
Right side							
mm. biceps brachii, brachioradialis and stump extensor muscle	σ_1	1.7	1.2	3.7	3.0	71	6.7
	σ_2	3.9	1.0	3.4	2.5	62	5.2
	σ_3	2.0	1.1	—	—	—	2.2
	σ	4.7	1.9	5.1	3.9	94	8.7
Left side							
mm. biceps brachii, brachioradialis and stump extensor muscle	σ_1	2.3	1.5	2.8	2.1	61	3.7
	σ_2	3.0	1.2	1.7	1.2	53	—
	σ_3	0.9	0.7	2.9	2.2	59	—
	σ	3.9	2.1	4.3	3.3	100	3.7

side. Differences between individuals are statistically significant for α, β and $A_{\max}$ of the right side and for all parameters except $A_{\max}$ of the left side. The standard deviation components obtained from the analyses of variance are shown in Table 15.

Comparison between Right and Left Side Muscles Yielding Normal EMG

Comparison of the right and left side parameter values in Table 13 shows all differences to be statistically significant except the following: α and $A_{\max}$ of m. biceps brachii, α of m. brachioradialis, and β and γ of the stump flexor muscle. Parameter values of the right side mm. biceps brachii and brachioradialis, and of the right stump flexor muscle tend to be lower than those of the corresponding left side muscles. For the stump extensor muscle the opposite relation was found.

Comparison between Muscles of Amputees Yielding Normal EMG and Muscles of Uninjured Controls

Statistically significant differences between the parameter values obtained for muscles of amputees, yielding normal EMG, and the corresponding values for uninjured controls are shown in Table 16. It is interesting to note that whenever statistically significant differences occur for right side as well as left side muscles, the deviations take place in the same direction. It is also interesting to note that—without exception—the low-frequency content of the amputee muscles, as measured by α, is low. This agrees with the also consistently low β values (although here, three of the six deviations are not large enough to be statistically significant).

As might be expected with regard to etiology, differences of the amputations, the deviation components listed in Table 15 differ—in absolute as well as relative magnitude—from those obtained for uninjured controls (Tables 2 and 10).

Simultaneous presentations of all significant differences between pairs of muscles with respect to the six spectrum parameters are given in Figures 6 and 7.

Comparison between Muscles of Amputees Yielding Neurogenic EMG and Muscles of Uninjured Controls

The parameter values of amputee muscles yielding neurogenic EMG could be compared to the corresponding values of uninjured controls

Table 16. Statistically significant differences between parameters of normal-EMG amputee muscles and uninjured control muscles. Positive values imply that amputee parameters are larger, negative values that they are smaller than control parameters (note that all average α and s values concerned are negative).

	Muscle	α(dB)	β(dB)	γ(dB)	s(dB/ octave)	f_s(Hz)	$A_{\max}$ (dB)
Right side	trapezius	—	—	—	—2.0	—	4.4
	biceps brachii	0.8	—0.9	—3.1	2.3	—52	1.7
	brachioradialis	3.0	—	—	—	—	—
	stump extensor	1.3	—	—	—1.5	48	—1.1
Left side	biceps brachii	1.9	—1.2	—2.0	0.8	—	—
	brachioradialis	2.7	—0.7	—	—0.8	45	—2.1
	stump extensor	3.9	—0.9	—	—1.6	149	—1.7

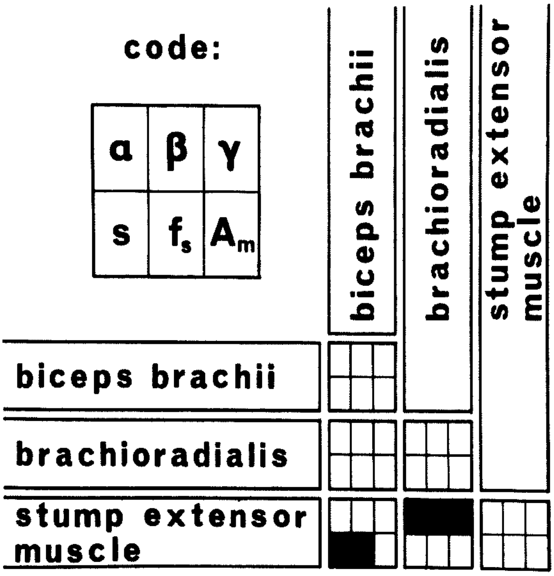

Figure 6. Significant differences (= filled rectangels) between pairs of right-side amputee muscles having normal EMG, with respect to α, β, γ, s, f_s and $A_{\max}$.

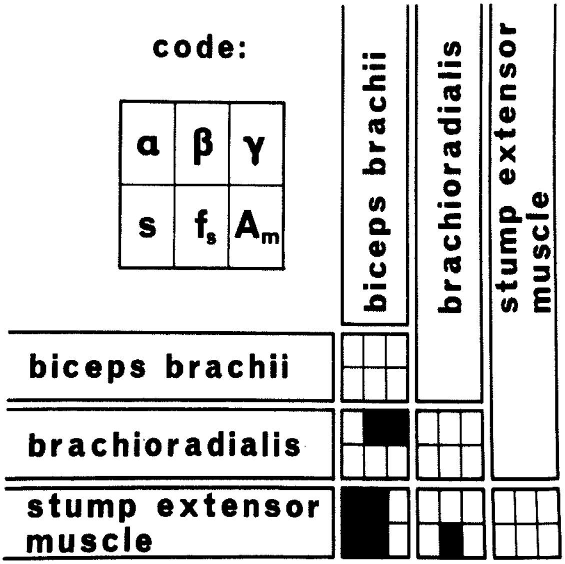

Figure 7. Significant differences (= filled rectangles) between pairs of left-side amputee muscles having normal EMG, with respect to α, β, γ, s, f_s and $A_{\max}$.

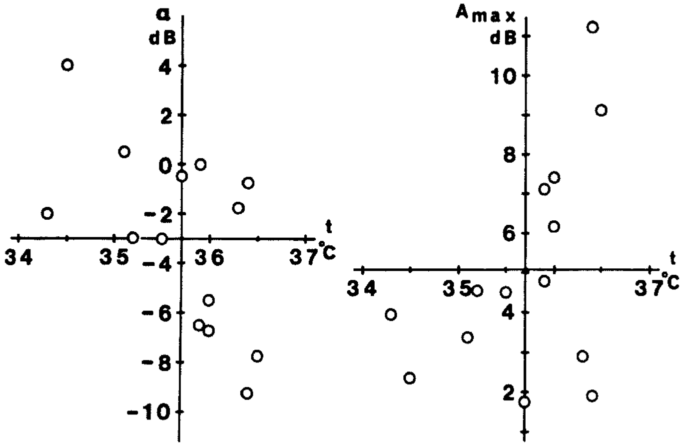

Figure 8. Scatter diagrams of parameters α and $A_{\max}$ vs. temperature t.

for the right and left side stump extensor muscles only. For these two two muscles all parameters except β of the right muscle show statistically significant deviations.

Influence of Muscle Temperature

Muscle temperature was measured in the stump extensor muscle of the 14 below-elbow amputees having normal EMG for that muscle. The temperature varied between 34.3 and 36.5° C; the mean value was 35.7° C. Inspection of scatter diagrams revealed no discernible temperature dependence of β, γ, s or f_s. As shown in Figure 8, parameters α and $A_{\max}$ are evenly distributed for temperatures above average (35.7° C). For lower temperatures, however, no low α or high $A_{\max}$ values were recorded. This implication of low-frequency content decreasing with temperature is particularly interesting in view of the increased percentage of polyphasic potentials at lower temperatures (reported by Buchthal et al. 1954). It should be noted, however, that increased action potential duration has also been reported for lower muscle temperature (Bentsen 1945, Buchthal & Pinelli 1952).

DISCUSSION

The number of muscles included in the present investigation may seem astonishingly high. In view of the urgent need of prosthesis control sites, however, an even more extensive set of muscles had been desirable. On the other hand, discomfort and pain caused by needle electrode insertions have limited the number of muscles investigated. This is, of course, particularly pronounced in the case of amputees, and is the reason why the groups of amputee muscles vary in size.

The present analysis of myoelectric signals yields information on the shape of the power spectrum. This way of describing the signal properties is particularly useful in prosthesis design work aimed at finding optimum preprocessing filters. The present investigation concentrates on the problems of intramuscular, intermuscular and interindividual variations of the shape of the power spectrum at a constant level of moderate contraction, yielding signals well above the background noise in the frequency range studied. The further problems of power spectrum variations with muscle load, which require additional extensive investigations, will be treated separately.

The power spectrum frequency range of greatest interest in prosthesis control has been stated by various authors to be the interval between 100 or 300 and 1000 Hz (Battye et al. 1955, Horn 1963, Hirsch et al. 1964, see also Kaiser et al. 1968). The low-frequency limit of about 100 Hz is determined partly by the risk of mains interference, partly by the relatively large erratic fluctuations encountered at lower frequencies. The high-frequency limit is determined by power spectrum roll-of, which causes the signal-to-noise ratio to deteriorate if frequencies much above 1000 Hz are included. Investigations of this power spectrum should thus cover a frequency range of about 50 to 2000 Hz. In order to achieve a reasonable data reduction, we have taken measurements at four points—corresponding to the average powers in octaves centered at 50, 200, 800 and 1600 Hz—within this range. Further data reduction, to three recorded points per electrode position, is obtained by performing all measurements at essentially the same level of contraction.

The measured values α, β, and γ can, of course, be converted into high-frequency asymptote slope and corner frequency—standard concepts of filter and circuit theory—in several ways. The fundamental method used in the present paper based on the cubic approximation in Eq. (1), has the advantage of being applicable in most cases. When the third-power curve did not display a finite maximum, which happened for about two per cent of the spectra, a parabola connecting the 50, 200 and 800 Hz points was used instead. The condition that the interconnecting curve has exactly the same slope as the high-frequency asymptote at 800 Hz was thus waived for these spectra. This procedure does not, of course, influence the α, β, γ or s values, and provides f_s and $A_{\max}$ values well within the range of variation of the other spectra. For five individual spectra (of a total of more than 5000), the 50, 200 and 800 Hz points were situated on a straight line, excluding the possibility of assigning maxima to the spectra. In view of the random measurement-error component, and in order to retain the irregularity of the spectra concerned, the α value obtained in these cases—typically about -11 dB—was increased by one dB. The origin of the extremely low α values (high low-freqency content as measured in the 50 Hz band) is not clear; the possibility of an artifact, e. g. mains interference, cannot, of course, be excluded.

Skeleton muscles in higher vertebrates have been divided in two types, red and white. The red muscles perform sustained contractions, and the white perform rapid, phasic movements (Denny-Brown 1929, Creed et al. 1932, Krüger 1952). The red and white muscle fibres constitute a complex mixture within the same muscle of the vertebrates.

Red and white muscles have previously been studied from the functional point of view, physiologically characterized by long and short contraction times, respectively. At that time it was justifiable to refer to slow and rapid muscles, as it was believed that all muscle fibres in a slow muscle performed sustained contractions, even though all fibres were not red.

The existence of different mononeurons with different functions, so-called phasic and tonic motoneurons, was later demonstrated on cat (Granit et al. 1956, Eccles et al. 1958). In the tonic motoneurons Eccles et al. (1958) found a long after-hyperpolarization potential causing a reduced level of excitation. These neurons thus fire at lower frequencies than the phasic motoneurons. The tonic neurons also have thinner fibres, and transmit the impulses at lower velocities. The type of motoneuron activating the muscle was considered decisive for the phasic or tonic action of the muscle.

By means of histochemical methods it has recently been proved on rat that with respect to function there are different muscle fibres (Kugelberg & Edström 1968, Edström & Kugelberg 1968). These authors showed that the phasic muscle fibres, mainly supplied with aerobe energy, were less easily fatigued. The tests were carried out by stimulating the rat muscle to such an extent that the circulation was not seriously affected. It was believed that the phasic muscle fibres were prevented from being unneccessarily activated in ordinary muscle contractions by innervation of special phasic motoneurons. A striking relation between the difference in fatiguability and the histochemically verified type of muscle was demonstrated in stimulating single motor units (Edström & Kugelberg 1968). It was found that individual motor units were largely uniform as regards muscle fibre type.

Tokizane & Shimazu (1964) proved that human muscle also contains phasic and tonic muscle fibres. These functionally different motor units are both present in all muscles studied by these authors, but with intermuscular variations between, for instance, facial muscles. Furthermore, phasic units were morphologically more spread than the tonic units, which were mainly situated in the central part of the muscle.

Kugelberg & Edström (1968) showed that stimulation producing fused contraction in rat muscle caused a considerable obstruction of the blood flow. Simultaneously a pronounced muscular fatigue rapidly developed, which was considered to be due to a failure of the neuromuscular transmission acting as a protection of the muscle fibre. At a lower frequency of stimulation the developing muscle fatigue depended on contractile elements being affected.

Dynamic changes of the myoelectric power spectrum during fatiguing isometric muscle contraction were investigated by Kadefors et al. (1967, 1968). The authors discussed the possibility that the decline of signal activity in the high-frequency range could be due to a drop-out of rapid motor units. These motor units probably correspond to the phasic, rapidly fatiguable units. The relation between muscular blood flow and power spectrum in sustained maximal contraction of the human muscle has recently been studied by Kadefors et al. (1969).

Although several mechanisms may conceivably be responsible for the differences in power spectrum shape, a number of the present results appear particularly interesting in view of the existence of functionally different types of motor units. Thus, mm. gastrocnemius and soleus, which are often referred to as typical examples of muscles having fast and slow muscle contraction rates, respectively, differ strikingly from other muscles. The *high-frequency* content (in the 800 and 1600 Hz ranges) of the m. gastrocnemius signal is significantly *less* than that of all the other eight muscles used for comparison, and the *low-frequency* content (in the 50 Hz range) of the m. soleus signal is also significantly *less* than that of all the other eight muscles. Thus, both muscles display extreme properties in the power spectrum domain also. The relatively small low-frequency content of the "slow"

m. soleus and the relatively small high-frequency content of the "fast" m. gastrocnemius are, however, not remarkable (since, for example, short-duration potential components may occur superimposed on action potentials of long durations, and short-duration action potentials may occur in periodical bursts).

SUMMARY

Power spectra of myoelectric signals for moderate, short-lasting muscle contractions were measured in 50 uninjured controls and 30 arm amputees, all males and aged 20 to 50 years. A method yielding the four average spectrum levels in octave bands centered at 50, 200, 800 and 1600 Hz was used.

In the control group, 11 right-side and 5 left-side limb muscles were studied. Statistically significant intramuscular (most important), intermuscular (next most important) and interindividual (least important) level differences were found. Differences between right and left sides were also significant.

In the arm amputee group spectrum differences were demonstrated between muscles having normal and neurogenic EMG, respectively. As for the control group, intramuscular, intermuscular, interside and interindividual differences were found for muscles having normal EMG.

Statistically significant power spectrum differences were found between control muscles and amputee muscles. This result was obtained for the normal-EMG as well as the neurogenic-EMG groups of amputee muscles.

No pronounced power-spectrum temperature dependence was observed, neither for control nor amputee muscles.

The four spectrum levels were also transformed into high-frequency asymptote slope and corner frequency of a piece-wise linear spectrum model. These transformed parameters displayed essentially the same statistically significant differences as the levels themselves.

The results are discussed with regard to optimal signal preprocessing in prosthesis control and with regard to the existence of functionally different types of motor units.

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Correspondence to:

Dr. P. Herberts
Dept. of Clinical Neurophysiology and Orthopaedic Surgery
Sohlgrenska Sjukhuset
University of Göteborg, Sweden