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The Amplitude Distribution of Surface EMG in Static and Intermittent Static Muscular Performance

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Summary. A measure of the variation of load on individual muscles or parts of muscles may be obtained by estimating the amplitude probability distribution function (APDF) of the myoelectric signal. In a study of elbow flexor muscular performance in static and intermittent static low level muscular contractions, the APDF was computed from the surface EMG obtained from the belly of the brachial biceps muscle. The APDF was also computed from the simultaneously recorded force signal. The APDF of the myoelectric signal and of the force signal were similar, indicating that the APDF of the myoelectric signal closely reflects the muscular load in non-fatiguing muscular contractions. The effect of the time constant in lowpass filtering when processing the surface EMG-signals was also studied. A suitable time constant appears to be in the range of 50–100 ms.

Key words: Amplitude distribution – Surface EMG – Muscular performance – Lowpass filtering

In vocational or ergonomic studies electromyography is commonly used to give information about muscular performance. In the evaluation of work load situations or positions, commonly used work-physiological parameters such as heart rate, oxygen consumption, or blood pressure may not reveal the load on individual muscles. With electromyographic techniques it is possible to estimate the load on individual muscles or parts of individual muscles. This estimation may be done by using the relationship between the myoelectric signal activity and the force produced by the muscle. Many investigations have dealt with this relationship, and it has been reported by some as linear (e.g., Bigland and Lippold, 1954) and as curvilinear by others (e.g., Vredenbregt and Rau, 1973).

In sustained contraction ultimately leading to muscular fatigue, increase of myoelectric activity is usually seen. Currier reported in 1969 a linear relationship in the progressive increase of electrical activity during a sustained static contraction of the anterior deltoid muscle. The growth of EMG during a sustained contraction as

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fatigue develops is well described by a linear-plus exponential form (Kuroda et al., 1970).

In vocational studies, the force of contraction of muscles usually fluctuates over a wide range of contraction levels. It may, therefore, be important in ergonomic investigations to get a measure of the distribution of the different levels of contraction. Such a measure may be obtained by evaluating the amplitude probability distribution function (APDF) of the myoelectric signal (Jonsson, 1976). The APDF of the myoelectric signal seems closely to reflect the work performed by the muscle (Hagberg, 1976). The random character of the surface EMG signal necessitates a preprocessing of the signal. By fullwave rectification and lowpass filtering, using a suitable time constant, it is possible to achieve a continuous recording of the mean EMG-level.

The amplitude probability at a certain level of contraction is the probability of the myoelectric activity being lower than or equal to that contraction level. The amplitude probability at a certain level can be expressed as the fraction of the total duration that the signal is lower than or equal to this level (Fig. 1). If this fraction is estimated at a large number of levels, a good estimate of the amplitude probability distribution function (APDF) is obtained.

In the APDF a value close to zero represents the force level of the lowest contraction level of muscular performance. A value close to unity shows the maximum contraction level produced by the muscle during the recording time. The me-

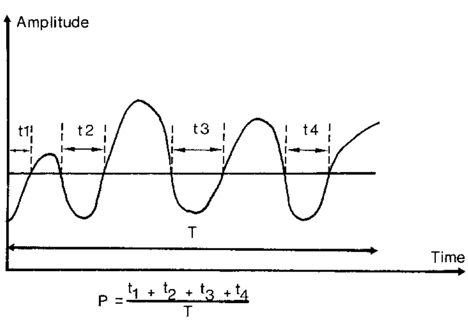

Fig. 1. The amplitude probability (**P**) for a signal at a predetermined level, where T represents the total duration of the time period studied, and t_1–t_4 represents the length of time that the signal is lower than or equal to the predetermined level

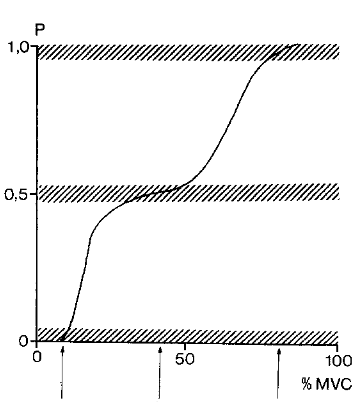

Fig. 2. From the estimated amplitude probability distribution function (APDF), it is possible to determine the lowest contraction level, indicated (**a**), the median force of contraction, indicated (**b**) and the maximum contraction level, indicated (**c**), produced by the muscles during the recording time

dian force of contraction during the recording time is represented by the probability 0.5 (Fig. 2).

To reduce interindividual differences, the contraction level can be expressed in per cent of the maximum voluntary force of contraction (% MVC). The EMG levels measured in per cent of MVC may be computed by regression in reverse on the EMG-force relationship.

The aim of this study was to (1) investigate the relation between the APDF of the myoelectric signal and the APDF of the muscular force performance, and to (2) investigate the influence of the lowpass filtering time constant in the APDF of the myoelectric signal.

Material and Methods

The investigation was set up with five healthy subjects, three males and two females, the ages of whom ranged between 20 and 34 years. The subjects performed their task in a sitting position. A forearm splint fixed the subject's right forearm semipronated with 90 degrees flexion of the elbow joint as well as the shoulder joint (Fig. 3). The forearm splint was connected directly to a force transducer. Myoelectric activity from the belly of the right biceps brachii muscle was picked up by bipolar Ag/AgCl electrodes.

The amplified signals (2 Hz—2.5 kHz) were displayed on an oscilloscope and on a Mingograph ink recorder for visual signal control. The myoelectric and force transducer signals were also recorded on tape.

To determine the subject's maximum voluntary force of contraction, the subject was called 24 h before the experimental session to perform three maximum voluntary contractions (MVC) of the elbow flexors in the apparatus described above. The maximum peak force measured at the wrist was regarded as the subject's MVC. The experimental session was started and ended by a series of static test contractions at the following force levels: 2.5, 5, 7.5, 10, 15, 20, 30, 40, and 50% of the subject's MVC, each of a duration of 10 s. This was done in order to establish the relationship between the force produced by the elbow flexors, measured at the wrist, and the myoelectric activity picked up from the right biceps brachii muscle. The muscular performances each subject had to perform during the experimental session were static and intermittent static contractions (Table 1).

The regression analysis of the relationship between the EMG-level and the force level in the test contractions, consisted of computing the power curve regression function. EMG and force levels were achieved by time means of the fullwave rectified and lowpass filtered signals. The APDF used was estimated with an instrument which measures the time that the analyzed signal is past a chosen comparator threshold level. The comparator threshold levels were chosen in per cent of MVC by regression in reverse of the EMG-force relationship.

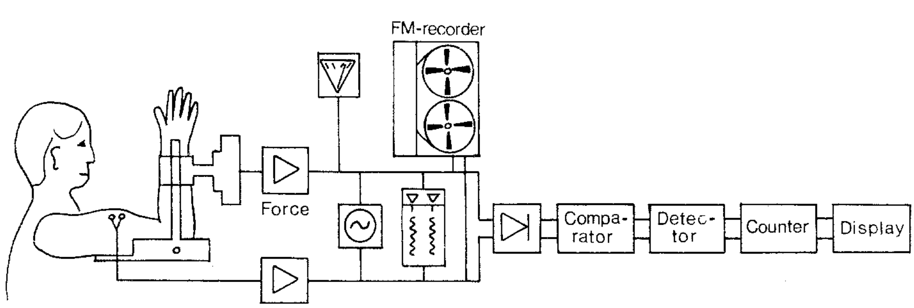

Fig. 3. Block diagram of the experimental set up and analysis procedure

Table 1. The different muscular performances used in the experiments

Type of contraction	Cycle	Duration
Static 5% of MVC	Continuous	5 min
Static 10% of MVC	Continuous	5 min
Intermittent static 5% of MVC	5 s contraction, 5 s rest	5 min
Intermittent static 10% of MVC	5 s contraction, 5 s rest	5 min
Intermittent static 5% of MVC	1 s contraction, 1 s rest	5 min
Intermittent static 5, 7.5, 10, 12.5, and 15% of MVC	5 s contraction, 5 s rest	5 min

The estimated APDF of the myoelectric signals and of the force signals were compared at probabilities of 0.1, 0.5, and 0.9, respectively, by *t*-test of correlated data.

To obtain the optimal time constant, when the EMG signals were lowpass filtered, lowpass filtering was performed at the following time constants: 5, 10, 50, 75, 100, 200, 500, and 1000 ms.

Results

The time mean of the absolute and lowpass filtered myoelectric signal during the test contractions expressed as a power function of static force level (in per cent of MVC) had a high correlation, Pearsons r ranged between 0.974 and 0.989 for the five subjects.

The estimated amplitude probability values of the myoelectric signals and the force transducer signals showed similarity in the different muscular performances studied (Fig. 4, Table 2), when using a 50 ms time constant in lowpass filtering of the myoelectric signal, and a 10 ms time constant in lowpass filtering of the force signal.

The dissimilarities between the amplitude values obtained from the myoelectric and force signals at probability 0.1, 0.5, and 0.9 are low. The null hypothesis, that the difference between the amplitude values in the APDF of the myoelectric signals and the force signals at probability 0.1, 0.5, and 0.9 are zero, could not be rejected ($t = 0.025$) for the five subjects.

The APDF curve recorded during the fifth minute of a muscular performance consisting of a 10% static contraction, was transposed to higher contraction values compared to the APDF-curve obtained during the first minute of the same muscular performance (Fig. 5). This phenomenon was not seen in the other types of muscular activity studied.

The amplitude probability values obtained from the myoelectric signals and the force signals were almost uniform when using time constants of 50, 75, and 100 ms in lowpass filtering of the myoelectric signal. In static contractions and in intermittent static contractions with long periods of relaxation, additional (longer) time constants of 200 and 500 ms gave similar amplitude probability values. In rapid intermittent static contractions, however, the time constants of 200 and 500 ms proved to be too long. When using shorter or longer time constants, respectively, than the time constants of 50, 75, and 100 ms the similarity between the APDF of EMG and force signal was degraded (Fig. 6).

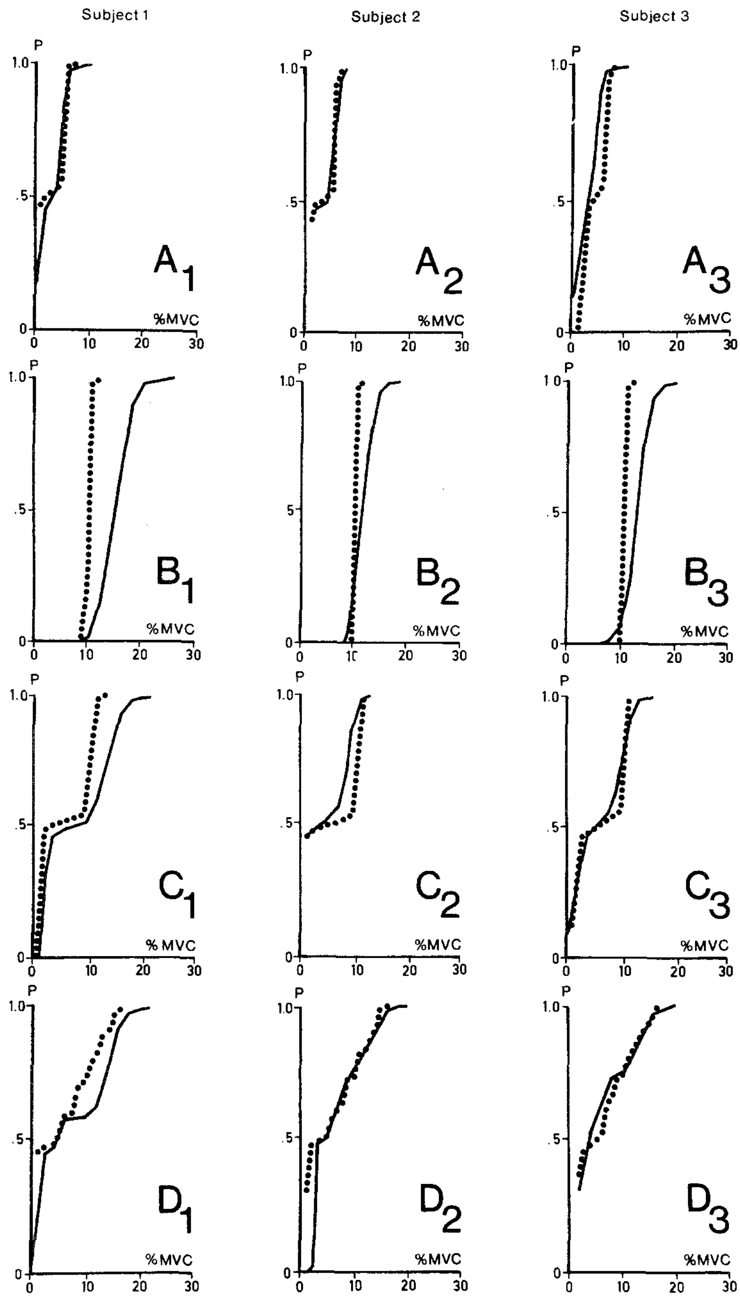

Fig. 4. The amplitude probability distribution function (APDF) for three subjects (males) where the "force functions" are represented by dotted lines and the "myoelectric functions" by solid lines. (P = Probability, MVC = Maximal voluntary contraction). A_{1-3} shows the APDF: s in a series of intermittent static contractions at 5% MVC (cycle: 5 s contraction, 5 s rest) by the three male subjects, B_1–B_3 the APDF: s in a continuous static contraction at 10% MVC, C_1–C_3 the APDF: s in a series of intermittent static contractions at 10% MVC (cycle: 5 s contractions, 5 s rest), D_1–D_3 the APDF: s in a "complex" series of intermittent static contractions (cycle: 5 s contractions, 5 s rest). The total duration of each experiment was 5 min

Table 2. The amplitude values of the fullwave rectified and lowpass filtered myoelectric signals (50 ms time constant) and force signals (10 ms time constant) of the five subjects (numbered 1–5) at probabilities 0.1, 0.5, and 0.9 for different muscular performances. The amplitude values are expressed in percent MVC of each subject (estimated by regression in reverse using the power function of the EMG – force relationship). In the intermittent static contractions the cycles were 5 s contraction, 5 s rest. The duration of each experiment was 5 min

Performance		0.1		0.5		0.9		Dissimilarity (EMG–Force)		
		EMG	Force	EMG	Force	EMG	Force	0.1	0.5	0.9
Continuous	1	3.5	5	6	5	7	5.5	– 1.5	+ 1	+ 1.5
static	2	3	5	4.5	5.5	5	6	– 2	– 1	– 1
contraction at	3	3	5.5	4.5	5.5	5.5	6	– 2.5	– 1	– 0.5
5% of MVC	4	3.5	4.5	4.5	5.5	5.5	6	– 1	– 1	– 0.5
	5	3.5	5	5	6.5	6.5	8	– 1.5	– 1.5	– 1.5
Continuous	1	9	9.5	11	10	13	11.5	– 0.5	+ 1	+ 1.5
static	2	11.5	9.5	15	10.5	18	11	+ 2	+ 4.5	+ 7
contraction at	3	11.5	11.5	13	11	15.5	11.5	0	+ 2	+ 4
10% of MVC	4	10	10.5	11.5	11	13.5	11	– 0.5	+ 0.5	– 2.5
	5	5.5	10.5	9	11.5	12	12	– 5	– 2.5	0
Intermittent	1	–	–	4	3.5	6	6	–	+ 0.5	0
static	2	–	–	3	2.5	5.5	6	–	+ 0.5	– 0.5
contractions at	3	0	1.5	3	4	5	6	– 1.5	– 1	– 1
5% of MVC	4	0	0	2.5	3.5	5.5	6	0	– 1	– 0.5
	5	–	–	3	3	7	8	–	0	– 1
Intermittent	1	–	–	3.5	5	10	11.5	–	– 1.5	– 1.5
static	2	1.5	0.5	7.5	4	15.5	11.5	+ 1	+ 3.5	+ 4
contractions at	3	0.5	0.5	5.5	6	12	11	0	– 0.5	+ 1
10% of MVC	4	0	0	4.5	5	9	11	0	– 0.5	+ 2
	5	–	–	4	5	11	12.5	–	– 1	– 1.5
Intermittent	1	–	–	5	5	14	14	–	0	0
static	2	–	–	5	6.5	15.5	14	–	– 1.5	+ 1.5
contractions at	3	–	–	4	6	14.5	14	–	– 2	+ 0.5
5, 7.5, 10,	4	–	–	6	4	13.5	13	–	+ 2	+ 0.5
12.5, and 15% of MVC	5	–	–	3	4.5	10.5	15.5	–	– 1.5	+ 5

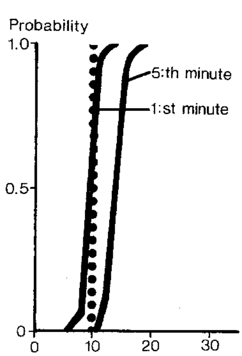

Fig. 5. The amplitude probability distribution function (APDF) for one subject (male) in a static contraction at a force level of 10% of MVC for the first minute and the fifth minute, respectively. The APDF of the force signal (dotted line) does not change in the interval studied

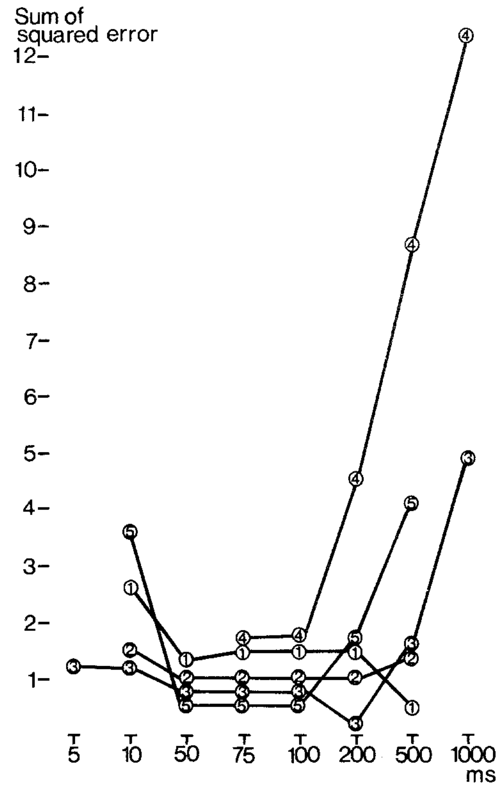

Fig. 6. The "error" of estimation of the contraction level from the myoelectric signals using different time constants in the lowpass filtering. The sum of the squared dissimilarity between the amplitude values at probabilities 0.1, 0.5, and 0.9 of the APDF (on the ordinate) obtained from the myoelectric signals at different time constants (on the abscissa) and from the force signals (time constant 10 ms). The five subjects performed a series of intermittent static contractions (cycle: 1 s of contraction, 1 s of rest) at a 5% contraction level for 5 min. The sum of the squared error at different time constants in the lowpass filtering of the myoelectric signals is for each subject (numbered 1–5) linked together by a solid line

Discussion

The present experimental set up with five subjects was used as a methodological model to study the amplitude probability distribution function (APDF) of the myoelectric signal, and the force produced by the elbow flexors expressed in relation to the maximum voluntary force of contraction of the same muscles.

The results show that it is possible to get a quantitative estimation of the variation of muscular load by calculating the APDF of the surface myoelectric signal for the muscular performance studied, provided that a suitable time constant is used in the lowpass filtering of the myoelectric signals and that fatiguing processes are not present. The APDF of the myoelectric signal gives information about the distribution of different contraction levels in the muscular performances studied.

The difference between the myoelectric and force signals tested by the t-test of correlated data, supports the hypothesis that the two estimated functions are similar. However, it is obvious from Table 2 and from Figure 4 that the APDF estimated from the myoelectric signals systematically overestimates the APDF of the force signal in continuous static contraction of 10% MVC. This overestimation or transposition of the APDF of the surface "absolute myoelectric signal", significant (t = 0.05) at probability 0.9, (by the t-test of correlated data), is probably due to a general increase in myoelectric signal amplitude, indicating early signs of muscle fatigue. These observations agree with the reports by Currier (1969) and Kuroda et al. (1970) who demonstrated an increase in surface EMG during sustained isometric contractions. In their experiments, the levels of static contractions were high, and the occurrence of this phenomenon at such low levels as 10% MVC needs further investigation.

The force signal follows the mechanical changes produced by the muscles and, hence, an acceptable time constant in the lowpass filtering of the force signal has to be short in comparison to the fastest mechanical changes. The rectification converts the myoelectric signal to a DC-signal with rapid fluctuations. The value of the instantaneous amplitude gives little or no information about the mean EMG-level. Lowpass filtering will smooth the signal, the degree of smoothing being determined by the time constant used. A long time constant results in information loss about the muscular performances in a mechanical action of short duration. A reasonable time constant proved to be no longer than 100 ms. The time constant used for lowpass filtering of the myoelectric signal also has to be long in comparison to the period of the predominant frequency band of the biceps muscle, 30–200 Hz (Scott, 1967), to reflect the mean EMG-level.

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