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Myoelectric Power Spectrum Dependence on Muscular Contraction Level of Elbow Flexors*

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Summary. The influence of the strength of contraction on surface recorded myoelectric power spectra was studied for three elbow flexors. Four subjects performed brief (3–5 s) isometric contraction levels (5–80% MVC). The experiment was repeated 23–26 times on different days. The surface myoelectric signal was recorded from the biceps brachii, the brachialis and the brachioradialis. By fast Fourier transform the myoelectric power spectrum was computed. The mean power frequency (MPF) was calculated and used as a single estimate of the myoelectric power spectrum. The MPF was found to increase with contraction strength with low level contractions. At levels in excess of 25–30% of MVC, the MPF became independent of contraction level. This dependence of the MPF on low level contractions is explained by tissue filtering effects and the recruitment order and distribution of motor units.

Key words: Electromyography – Muscle contraction – Exercise – Isometric fatigue – Frequency analysis

Introduction

Evaluation of muscular fatigue during work has recently gained an increasing interest. Particularly, changes in the myoelectric power spectrum have been shown to be well correlated to development of muscle fatigue (Lindström et al. 1977; Viitasalo and Komi 1977; Hagberg 1981b). It has been suggested that changes in the myoelectric power spectrum may be used as an indicator of muscle fatigue for ergonomic purposes (Lindström et al. 1977). However, in occupational situations, the force of contraction of muscles usually fluctuates

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over a wide range of contraction levels. The influence of contraction force on the myoelectric power spectrum may thus be important.

In contraction, the tension developed by the muscle can be graded both by changing the number of active motor units and by changing the firing frequencies of the active motor units. Recruitment, that is an increase in the number of active motor units, has been reported to be the dominant factor in increasing muscle tension in low level contractions (Milner-Brown and Stein 1975). In the surface electromyogram, recruitment and increase in the firing frequencies (rate coding) are seen as an amplitude increase of the surface myoelectric signal (Milner-Brown and Stein 1975). In the biceps brachii muscle, units of low threshold force were reported (Clamann 1970) to have a wide frequency range and tended to be located deep in the muscle, in contrast to the high threshold units which were located more superficially.

Since the distribution of low and high threshold motor units may not be uniform in a muscle, recruitment of motor units may influence the power spectrum of the surface recorded EMG due to tissue filtering effects. If the myoelectric power spectrum is dependent on contraction level, it would be a limiting factor in the use of power spectrum analysis as a diagnostic tool for muscle fatigue evaluation in occupational situations. It would also be necessary in ergonomic investigations of fatigue to evaluate the contraction level when changes in the myoelectric power spectrum require interpretation.

The aim of the present investigation was to determine whether the surface myoelectric power spectrum is dependent on the force of muscular contraction.

Material and Methods

Subjects

Four healthy males with a mean age of 24.3 years (range 21–24 years) volunteered to take part in the investigation. The mean isometric elbow flexion strength measured at the wrist was 343.7 N (range 304–383 N). All the subjects were thoroughly informed of the experimental procedures before consenting to participate.

Isometric Strength

The subjects performed the strength measurements in a sitting position with the forearm semipronated and 90 degrees of foward flexion in the shoulder (Fig. 1). A brace at the wrist was connected to a force transducer by a thin wire. The maximal voluntary contraction (MVC) was measured by a strain gauge dynamometer (Bofors) during isometric elbow flexion at an angle of 90 degrees. The best of three consecutive maximal voluntary contractions was considered to be the best estimate of the subjects maximal isometric strength.

Experimental Procedures

A series of brief (3–5 s) isometric elbow flexions (Fig. 1) at nine randomly assigned contraction levels of 5, 10, 15, 20, 25, 30, 40, 50, and 80% of MVC were performed by the subjects. A one minute

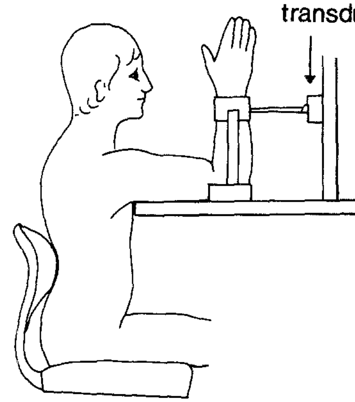

Fig. 1. The subjects position during the experiments

rest was given between the contractions. Only one series of nine contractions was carried out per 24-h period by any subject. All subjects performed 23–26 series of brief isometric contractions on each of 23–26 different days.

EMG-recordings

Myoelectric activity was picked up by Beckman miniature size surface electrodes – bipolar and set parallel to the muscle fibres – from the common belly of biceps brachii, the lateral part of brachialis, and the brachioradialis. The silver/silver-chloride disc electrodes had a 4 mm diameter area of contact. The interelectrode distance was 20 mm. Before the electrodes were attached, the skin area was dry shaved and rubbed into redness with alcohol and ether (4 : 1). Amplification of the myoelectric signal was obtained with a bandwidth of 0.2 Hz–2 kHz, and a second order filter provided a lower cut-off frequency at 2 Hz. The amplifier gain was adjusted at each contraction level to obtain similar amplitude levels in the recordings. Amplifier input impedance was 20 megaohm. The amplified EMG signals were recorded on a Bell and Howell FM-tape recorder with a bandwith of 0–2.5 kHz at the recording speed employed of 7.5 inches/s. For signal quality control the EMG signals were also displayed on an oscilloscope and on a Mingograph ink recorder.

EMG-analysis

The mean power frequency (MPF) (synonymous with mean spectral frequency) was used as a single estimate of the myoelectric power spectrum (Lindström et al. 1977; Komi and Tesch 1979; Petrofsky 1979). The myoelectric signals were lowpass filtered with a 330 Hz high frequency cut-off and sampled in 1.024 s samples at a rate of 1 kHz into a Hewlett Packard 21-Mx digital computer. On sample from each of the three muscles was obtained approximately between the 2nd and the 3rd second of the brief isometric contractions. The power spectrum (PS) was obtained using fast Fourier transform (FFT) techniques. The MPF was calculated through the formula $MPF = \int f PS(f)\, df / \int PS(f)\, df$ (Winter et al. 1979).

Statistical Analysis

A SPSS computer program (Nie et al. 1975) was used for linear regression analysis between MPF and the contraction level. By logarithmic transformation of data, a multiple power function regression was obtained between MPF and contraction level for the muscles investigated.

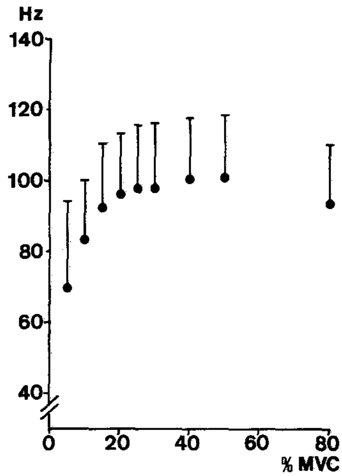

Fig. 2. Mean values and + 1SD of the mean power frequency of the surface recorded myoelectric signal from the biceps brachii for different contraction levels in four subjects. The contraction levels are in per cent of the maximal voluntary contraction (%MVC). Number of measurements: 845

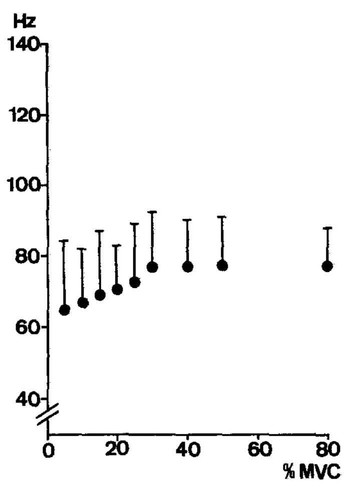

Fig. 3. Mean values and + 1SD of the mean power frequency of the surface recorded myoelectric signal from the brachialis for different contraction levels in four subjects. The contraction levels are in per cent of the maximal voluntary contraction (% MVC). Number of measurements: 549

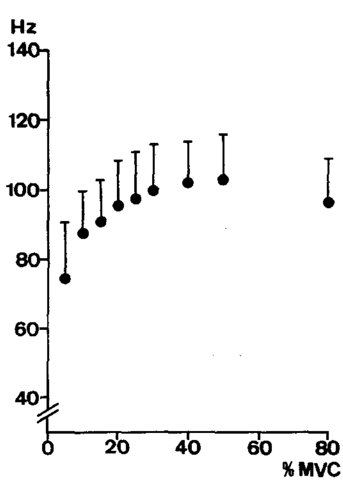

Fig. 4. Mean values and + 1SD of the mean power frequency of the surface recorded myoelectric signal from the brachioradialis for different contraction levels in four subjects. The contraction levels are in per cent of maximal voluntary contraction (% MVC). Number of measurements: 549

Table 1. Linear regression of MPF versus contraction level for the biceps brachii muscle. The contraction levels are in per cent of MVC (% MVC)

Contraction levels in % MVC	Correlation R	Significance of regression p-value (one-tailed)	Slope coefficient	Intercept	Number of measurements	Mean MPF	Standard deviation of MPF
5–15	0.431	0.001	2.302	58.7	282	81.7	21.8
5–20	0.459	0.001	1.777	63.0	376	85.2	21.7
5–25	0.460	0.001	1.396	66.8	470	87.8	15.0
5–30	0.438	0.001	1.092	70.4	563	89.5	17.5
5–40	0.419	0.001	0.790	74.7	657	91.0	20.7
5–50	0.393	0.001	0.576	78.2	751	92.2	24.4
5–80	0.245	0.001	0.227	85.4	845	92.4	20.5
40–80	0.187	0.002	−0.191	109.0	282	98.2	17.3
30–80	0.125	0.015	−0.117	104.0	375	98.1	17.5
30–50	0.060	0.315	0.128	94.6	281	99.7	17.4
25–50	0.068	0.187	0.124	94.8	375	99.3	17.4
20–50	0.095	0.040	0.153	93.5	469	98.6	17.4

Results

For all three elbow flexors the average mean power frequency (MPF) was lower at low contraction levels when compared with higher contraction levels (Figs. 2–4). Linear regression of the relationship between MPF and contraction level showed a relative MPF independence of contraction at levels of 20–50% of MVC for the biceps muscle (Table 1). At levels of 5–25% of MVC the highest correlation between MPF and contraction level was obtained (Table 1). The individual increase in average MPF of the biceps with contraction level varied slightly from subject to subject (Figs. 5–8). However, the increase in average MPF with contraction level at low tensions for all subjects is obvious.

For brachialis, the highest correlation between MPF and contraction was found between the levels of 5–40% of MVC (Table 2). Non-significant ($p > 0.05$, two-tailed test) correlation existed with levels of 20–80% of MVC.

The brachioradialis muscle showed the highest correlation ($R = 0.5143$) between MPF and contraction between levels of 5–40% of MVC (Table 3). At levels between 30–50% of MVC the regression of MPF versus contraction level was not significant ($p > 0.05$, two-tailed test).

The slopes of the MPF versus contraction level were steepest at the lowest contraction levels (5–15% of MVC) for all subjects and muscles. As higher contraction levels were included in the regression the slope coefficient decreased. The biceps brachii revealed higher slope coefficients than the other two muscles for the regression MPF versus contraction level when low level contractions were included in the regressions. For all three muscles investigated, a negative slope was found for the regression of MPF against contraction at levels of 40–80% of MVC. This phenomenon was due to a lower MPF at 80% of MVC compared to the MPF at 40 and 50% of MVC.

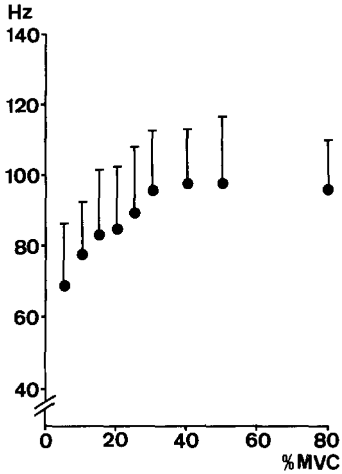

Fig. 5

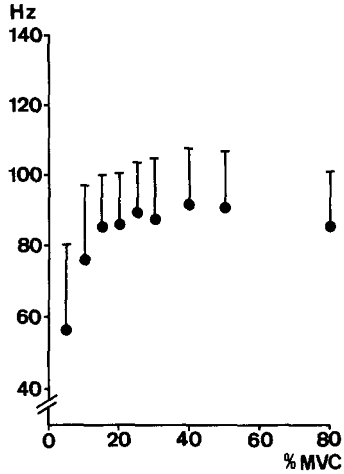

Fig. 6

Fig. 5. Mean values and + 1SD of the mean power frequency of the surface recorded myoelectric signal from the biceps brachii in subject RH, for different contraction levels. The contraction levels are in per cent of the maximal voluntary contraction (% MVC). Number of measurements: 207

Fig. 6. Mean values and + 1SD of the mean power frequency of the surface recorded myoelectric signal from the biceps brachii in subject SA, for different contraction levels. The contraction levels are in per cent of the maximal voluntary contraction (% MVC). Number of measurements: 199

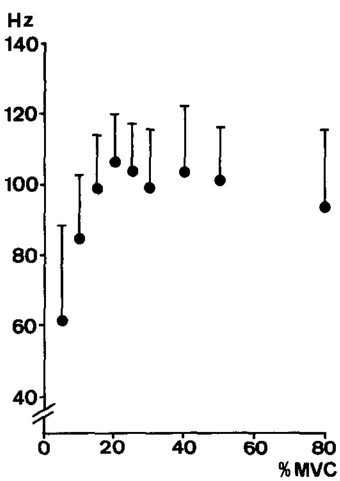

Fig. 7

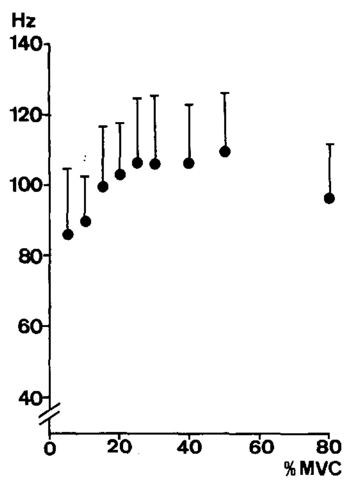

Fig. 8

Fig. 7. Mean values and + 1SD of the mean power frequency of the surface recorded myoelectric signal from the biceps brachii in subject LL, for different contraction levels. The contraction levels are in per cent of the maximal voluntary contractions (% MVC). Number of measurements: 205

Fig. 8. Mean values and + 1SD of the mean power frequency of the surface recorded myoelectric signal from the biceps brachii in subject LB, for different contraction levels. The contraction levels are in per cent of the maximal voluntary contraction (% MVC). Number of measurements: 234

Table 2. Linear regression of MPF versus contraction level for the brachialis muscle. The contraction levels are in per cent of MVC (% MVC)

Contraction levels in % MVC	Correlation R	Significance of regression p-value (one-tailed)	Slope coefficient	Intercept	Number of measurements	Mean MPF	Standard deviation of MPF
5–15	0.111	0.137	0.479	62.4	181	67.1	17.6
5–20	0.142	0.026	0.423	62.8	245	68.2	16.7
5–25	0.172	0.003	0.406	63.0	305	69.1	16.7
5–30	0.234	0.001	0.456	62.4	366	70.4	16.7
5–40	0.261	0.001	0.381	63.5	429	71.4	16.4
5–50	0.257	0.001	0.293	64.9	488	72.1	16.2
5–80	0.232	0.001	0.165	67.6	549	72.6	15.7
40–80	0.002	0.001	−0.001	77.2	184	77.1	12.4
30–80	0.002	0.982	0.001	77.0	244	77.1	13.1
25–80	0.061	0.289	0.043	74.3	304	76.3	13.8
20–80	0.116	0.026	0.080	72.1	368	75.3	13.9

Table 3. Linear regression of MPF versus contraction level for the brachioradialis muscle. The contraction levels are in per cent of MVC (% MVC)

Contraction levels in % MVC	Correlation R	Significance of regression p-value (one-tailed)	Slope coefficient	Intercept	Number of measurements	Mean MPF	Standard deviation of MPF
5–15	0.446	0.001	1.630	68.1	181	84.4	14.9
5–20	0.494	0.001	1.321	70.7	245	87.3	15.0
5–25	0.508	0.001	1.095	73.0	305	89.4	15.2
5–30	0.5142	0.001	0.920	75.0	366	91.1	15.2
5–40	0.5143	0.001	0.698	78.2	429	92.7	15.2
5–50	0.502	0.001	0.541	80.8	488	94.0	15.3
5–80	0.325	0.001	0.221	87.4	549	94.2	15.0
40–80	−0.233	0.001	−0.169	109.8	183	100.3	12.4
30–50	0.1094	0.140	0.162	95.1	183	101.5	12.0
25–50	0.153	0.017	0.197	93.5	243	100.6	12.2

The variance of MPF at different contractions levels was greater at the lowest contraction levels (5–15% of MVC) than at the higher contraction levels. A multiple regression correlation (r) between MPF and contraction level for the three elbow flexors was found to be 0.559 using logarithmic transformed data (1.943 measurements).

Discussion

In the recording of myoelectrical signals for frequency analysis one has to make sure that artifacts are not present. Especially with low level contractions using high amplification, "hum" may influence the mean power frequency (Winter et al. 1979). In the present investigation great care was taken in this respect, and all low level recordings were visually monitored for this with the signals displayed both on the oscilloscope and on the ink recorder.

A rise in muscle temperature increases the MPF (Petrofsky 1979; Petrofsky and Lind 1980b) due to effects on electrical resistance of the sarcolemma (Fink and Lüttgau 1976). During an isometric contraction, the increase in muscle temperature is a function of contraction level and duration (Edwards et al. 1975). The influence of muscle temperature on MPF was probably small, and negligible in these experiments due to the short duration of the contractions and the rest periods in between contractions and days of testing, and the random assignment of the different contraction levels.

Figures 2–4 of MPF versus contraction level indicate a non-linear function. Also a high correlation was obtained using logarithmic transformed data (power function regression). It also appears from Figs. 2–4 that the relationship between MPF and contraction level is approximately linear at low levels. Thus to evaluate the slope coefficient of MPF versus contraction strength at low levels and to determine whether a correlation existed between MPF and contraction strength at high levels, linear regression using nontransformed data appeared appropriate. Also, the constant variance of MPF favored the use of non-transformed data in the statistical evaluation (Chatterjee and Price 1977). The significant increase of MPF with tension found in the present study is probably mainly an effect of tissue filtering. The low frequency energy of the myoelectric signals has a greater ability to penetrate the tissues and is thus also easier to record by surface electrodes (Deluca 1979). Clamann (1970) found for the biceps brachii that larger motor units were located near the surface. Low threshold motor units are associated with small nerves (Freund et al. 1975), that is with small motor units. In a contraction where increasing tension is demanded, recruitment of increasingly larger motor units will occur (Milner-Brown et al. 1973a). For the biceps brachii we can thus assume that some of the low threshold motor units are located deep in the muscle. These units will predominantly contribute to the low frequency part of the myoelectric spectrum, since with bipolar surface electrodes the tissues act as a low pass filter (Lindström et al. 1970). When the distance between the active fibers and the electrodes decreases, the band width of the tissue filter increases. As larger motor units supercifically located are recruited, there are more motor units close to the electrodes, and an increase in higher frequency components of the myoelectric power spectrum can be expected. Furthermore, as the firing frequencies of the superficially located larger motor units increase, the myoelectric power spectrum influence of low frequency components on the MPF from deeply located muscle fibers decreases. Thus the surface recorded myoelectric power spectrum will change with the level of contraction where the tension developed is graded mainly by recruitment.

Recruitment of motor units occurs principally at low contraction levels

(Milner-Brown and Stein 1975; Gydikov and Kosarov 1974). Milner-Brown at al. (1973b) reported that the first dorsal interosseus muscle in two subjects had thresholds for recruitment between 1.5 and 2.0 kg of load, which corresponds approximately to 30–40% of MVC. Gydikow and Kosarov (1974) reported that almost no recruitment occurred for the biceps brachii muscle above 60% of MVC. Clamann (1970) found no recruitment contraction levels above 75% of MVC. In the present investigation almost no increase in MPF was noted above 25–30% of MVC, thus corresponding to the approximate level where recruitment strongly decreases (Milner-Brown et al. 1973b). The high slope coefficients found a low contraction levels for the regression of MPF versus contraction strength is thus probably due to the large recruitment of motor units versus rate coding.

Petrofsky and Lind recorded surface electromyograms from the belly of the flexor carpi radialis muscle (1980a) and the brachioradialis muscle (1980b) during isometric exercise using a handgrip dynamometer, and reported no significant differences in the centre frequencies ($p > 0.05$) for the tensions examined. Their results at first seem to contradict the findings of the present investigation. However, there are many factors that could explain the difference; 1) Petrofsky and Lind did not record prime movers, the flexor carpi radialis stabilizes the wrist during power grip, the brachioradialis muscle does not cross the radiocarpal joint (Rasch and Burke 1967; Hollinshead 1976). Thus the actual contraction level for the muscle in per cent MVC may differ from the per cent MVC exerted in power grip. 2) The number of measurements for each tension was also relatively small (16–20) in Petrofsky's and Lind's investigations, whereas in the present investigation 80–100 measurements were obtained at each tension for the biceps brachii. 3) Furthermore, the distribution and recruitment of motor units may differ between flexor carpi radialis, the distal end of the brachioradialis muscle and the muscles used in the present investigation. Increase of MPF with tension to 60% of MVC has been reported for the lower portion of m. rectus femoris (Komi and Viitasalo 1976).

At the highest contraction levels (40–80% of MVC) a significant negative slope was found for the three muscles, due to low MPF at the 80% of MVC contraction level. Despite the short duration (3–5 s) of contraction, fatigue remains the most likely explanation for the finding of low MPF at the 80% of MVC contraction level. A shift in the power spectra towards lower frequencies has been shown during fatiguing contractions (a.o. Lindström et al. 1977; Petrofsky and Lind 1980b). The predicted endurance time for an 80% MVC isometric contraction is only 29 s (Hagberg 1981b). The electromyographic signs of muscle fatigue have been reported as developing within a few seconds at lower contraction levels (Hagberg 1981a).

The correlation of MPF versus force is poor, although significant, due to the large variance in MPF: the use of MPF as an indicator of contraction level is thus contraindicated. In occupational situations contraction levels are mostly at low levels and fluctuate with time, although they may be fatiguing. When using myoelectric power spectrum analysis in vocational electromyography the fluctuating contraction levels during work may disturb the interpretation of changes in EMG spectra.

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