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Evaluation of the amplitude and frequency components of the surface EMG as an index of muscle fatigue

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The frequency components and amplude of the surface electromyogram (EMG) were measured during both 3-s (tensions of 5–100% of the maximum voluntary contraction (MVC)) and fatiguing contractions at 25, 40 and 70% MVC in the handgrip, biceps, adductor pollicis and quadriceps muscles in six male subjects. For the handgrip and biceps muscles, the experiments were repeated at three different muscle lengths: the length at which the muscle was able to exert its maximum isometric strength, and the muscle length above and below that length which corresponded to a length at which the muscle could exert 80% of it maximum. The frequency components of the EMG were the same during brief fatiguing isometric contractions in any of the muscles examined here as long as the muscles contracted near their optimal length. Shortening the muscle length prior to contraction caused an increase in the power in the low frequencies of the EMG power spectra while stretching a muscle had the opposite effect during isometric contractions. The amplitude of the EMG during brief and fatiguing contractions were similar for all muscles except the biceps. The biceps showed a non-linear relation between the amplitude of the EMG and tension during brief isometric contractions and to a lesser extent during fatiguing contractions.

1. Introduction

The surface electromyogram (EMG) is a potentially attractive tool for the non-invasive measurement of the tension developed in a muscle and the degree of muscle fatigue. Its use has been severely restricted, however, because of large differences in both the amplitude and frequency components of the EMG between subjects and for the same subjects tested at different times.

In studying the surface EMG as an indicator of impending fatigue, Kogi and Hakamada (1962) reported that when a muscle began to fatigue, there was an increase in the amplitude in the low frequency range and a reduction in the amplitude in the high frequency range of the electromyogram. Using this information, a number of investigators have attempted to construct fatigue indices based on the ratios of the low and high frequency components of the surface EMG during exercise (Kogi and Hakamada 1962, Kaiser and Petersén 1965, Sato 1965, Kadefors *et al.* 1968). The large variability in these ratios due to electrode placement, muscle temperature and a variety of other circumstances, however, makes this technique hard to use.

Fatigue indices of greater reliability have been developed using filter bank analysers (Eason 1960, Örtengren *et al.* 1975, Sultan and DeLuca 1978, Petrofsky 1980a) but these have an inbuilt error due to the long time constants which are commonly associated with the response times of low frequency active filters. Further, since muscle temperature can effect the frequency components of the EMG, environmental

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temperature variations can shift the predominant power in the EMG spectra outside of the range of set low and high frequency filters (Petrofsky and Lind 1980). A more accurate technique uses digital computers to process the EMG. A large number of frequency components can be analysed through calculation of the Fourier power spectra of digitized EMG samples (Lindström *et al.* 1970, 1977, Petrofsky *et al.* 1975, 1977, Petrofsky and Lind 1980). But even with this technique the problem of data reduction is still present because of the large number of frequency harmonics analysed by the computer. For simplicity, the median or centre frequency of the Fourier power spectrum (that frequency above and below at which the power in the spectrum is equal) can be calculated. Since the centre frequency is relatively independent of the tension developed by a muscle during brief isometric contractions (Viitasalo and Komi, 1977, Petrofsky and Lind, 1980), it would appear that the centre frequency could potentially be an excellent fatigue index.

Petrofsky *et al.* (1975, 1978, 1980) found an almost linear reduction in the centre frequency of the Fourier Power Spectra with time in the handgrip muscles during fatiguing isometric contractions. In the biceps muscle, Lindström and colleagues have shown an almost linear but somewhat exponential decrease in centre frequency (Lindström *et al.* 1977). Similar results were demonstrated by Stulen and DeLuca (1978).

Therefore, although the centre frequency of the EMG appears to be an attractive tool with which to assess muscle fatigue, the problem still remains that different results are found in different muscles. Therefore, if the centre frequency of the EMG power spectrum is to be used as a fatigue index, the mechanism of the variability and the change in centre frequency in different muscle groups throughout the duration of fatiguing exercise must be thoroughly explored.

The purpose of the present investigation was to examine the changes in the frequency and amplitude components of the surface EMG in various muscles and muscle groups with different muscle masses during brief and fatiguing isometric contractions. One possible factor which might cause the amplitude and frequency components to vary within a muscle is the muscle length. When joints are moved to various positions, muscles change length and this causes changes in sarcolemma diameter and length. The ultimate effect of this on the conduction velocity of action potentials and the amplitude and frequency components of the EMG has not been thoroughly explored. Therefore, the amplitude and frequency components of the EMG were measured on four muscles throughout the duration of fatiguing exercise and in two muscles the relationship between muscle length and the amplitude and frequency components of the EMG was further explored.

2. Methods

2.1 *Isometric strength and endurance*

Isometric strength and endurance were determined with strain gauge type isometric dynamometers for the handgrip (Clarke *et al.* 1958), adductor pollicis muscles (Petrofsky 1981), for the quadriceps muscles (Petrofsky *et al.* 1975) and the biceps muscles (Petrofsky and Phillips 1981) as described elsewhere. During isometric contractions of the handgrip, biceps and quadriceps muscles, the elbow and knee were kept bent at an angle of 90°. In all experiments, the limb which was under study was bare and the room temperature was maintained constant at 22 ± 2°C. Isometric strength in all cases was measured as the largest of three brief maximal isometric contractions (less than 3 s). The largest of these contractions was called the maximum voluntary contraction of the muscle (MVC). In some experiments, brief (3 s) isometric contractions were sustained at various proportions of the MVC established on each day. In other experiments, isometric contractions were sustained to fatigue at various proportions of the MVC established on each day. The endurance time in these experiments was defined as that length of time the subject could maintain a given target tension established at a percent of the MVC until, through fatigue, the target could no longer be sustained. Only one fatiguing isometric contraction was exerted in a 24-hour period.

2.2. *Electromyogram*

The surface electromyogram was recorded from the active muscle by two bipolar silver–silver-chloride disk electrodes spaced 2 cm apart. A differential amplifier with an input impedance of $10^8\ \Omega$ was used to preamplify the EMG prior to storage on an FM tape recorder. Analysis of the EMG involved sampling 1·5 s periods of the EMG on a digital computer (sampling rate of 1024 samples/s) and storing these digitized samples. The samples were analysed by using a fast Fourier transform (FFT) to calculate the amplitude of the harmonic components of the EMG from a fundamental frequency of 4 Hz through the first 128 harmonics (final frequency 512 Hz). From the harmonic components of the EMG, the centre frequency of the Fourier power spectrum was calculated as a representative frequency for all of the frequency components of the EMG. A complete description of this procedure is given elsewhere (Petrofsky 1980 b). The amplitude of the EMG was computed as the R.M.S. amplitude of the same digitized data.

2.3 *Subjects*

The subjects in this study were six male volunteers whose ages ranged from 22 to 28 years. All subjects were medically examined prior to the study including an ECG stress test on a treadmill and a resting pulmonary function test. All experimental procedures were explained in detail to each subject who then signed a statement of informed consent. All protocols were approved by the committee on human experimentation.

2.4. *Isometric training*

Before any recording of experimental data all subjects were thoroughly trained to exert a maximal effort and to sustain submaximal efforts to fatigue. Training involved the measurement of maximal isometric strength followed, 30 minutes later, by a series of five fatiguing isometric contractions at a tension of 40% MVC; 3-min rests were allowed between contractions. This procedure was repeated on Monday, Wednesday and Friday of successive weeks until the coefficient of variation of the endurance determinations on a particular day was reduced to less than 5%. Typically, no systematic change in strength occurred during the training period. The total training period for each muscle group ranged between 4 and 6 weeks.

2.5. *Experimental procedures*

Two of the experiments were performed as outlined below. In the first series of experiments, the relationship between the tension developed by the muscle during brief isometric contractions and the amplitude and frequency components of the EMG were determined in each of the four muscles. In addition, fatiguing isometric contractions were sustained at 25, 40 or 70% MVC in each of these same muscle groups and the changes in the amplitude and frequency components of the EMG throughout the duration of the contractions were also assessed. On any one experimental day, only one contraction was sustained to fatigue in any one muscle. The order of presentation of the tensions for each of the six subjects and the experimental procedures was totally randomized and done in replicate.

In the second series of experiments, the effect of muscle length on the amplitude and frequency components of the EMG during brief and sustained isometric contractions was examined. The entire series of experiments described above was repeated for the handgrip and biceps muscles. Here, however, the muscle contracted at three different lengths. A series of MVCs was performed with the handgrip and biceps dynamometer adjusted to allow the handgrip and biceps to contract at different muscle lengths. This was accomplished by presetting the grip size of the handgrip dynamometer at different lengths prior to the contractions and setting the elbow at preset angles between 140 and 30° prior to biceps contractions. The optimal elbow angle and handgrip size were then established at which the muscles developed their greatest isometric strength (P_{max}). This handgrip size and elbow angle was then used to set the first series of experiments in which the relationship between the amplitude and frequency components of the EMG during brief and fatiguing isometric contractions was established. This same procedure was repeated at the elbow angle and handgrip size and below the optimal length at which the muscle developed 80% P_{max}. Again here, subjects were asked to exert brief isometric contractions at tensions up to 100% MVC (the MVC established at that elbow angle or handgrip size) and then performed fatiguing isometric contractions at 25, 40 or 70% MVC. Only one experimental procedure was accomplished on a given day and all experiments were done in replicate and randomized for each of the six subjects.

2.6. *Statistical analysis of data*

Statistical analysis of the data involved in calculations of means, standard deviations, unpaired t-tests and regression lines. The level of significance was chosen at $P<0.05$.

3. Results

3.1. *Series 1*

The isometric strength and endurance of the four groups of muscles in the series 1 experiments is shown in the table. There was a linear relationship between the amplitude of the EMG and tension during brief isometric contractions at fractions of the MVC for the handgrip, adductor pollicis and quadriceps muscles as is shown, for example, in the handgrip muscles in figure 1. Statistical analysis of the three regression lines relating EMG amplitude and muscle tension showed no significanct difference between the slopes of the lines. In contrast, the biceps (figure 2) had a non-linear

Strength and endurance of muscles (mean ± S.D. in six subjects)

	Adductor pollicis	Handgrip muscles	Biceps	Quadriceps
MVC (Kg)	5·7 ± 0·48	53·99 ± 4·9	38·66 ± 7·1	43·61 ± 9·7
Endurance 25% MVC (s)	551 ± 162	368 ± 116	410 ± 161	402 ± 196
Endurance 40% MVC (s)	263 + 74	164 ± 46	264 ± 121	161 ± 31
Endurance 70% MVC (s)	81 ± 16	48 ± 11	73 ± 13	68 ± 19

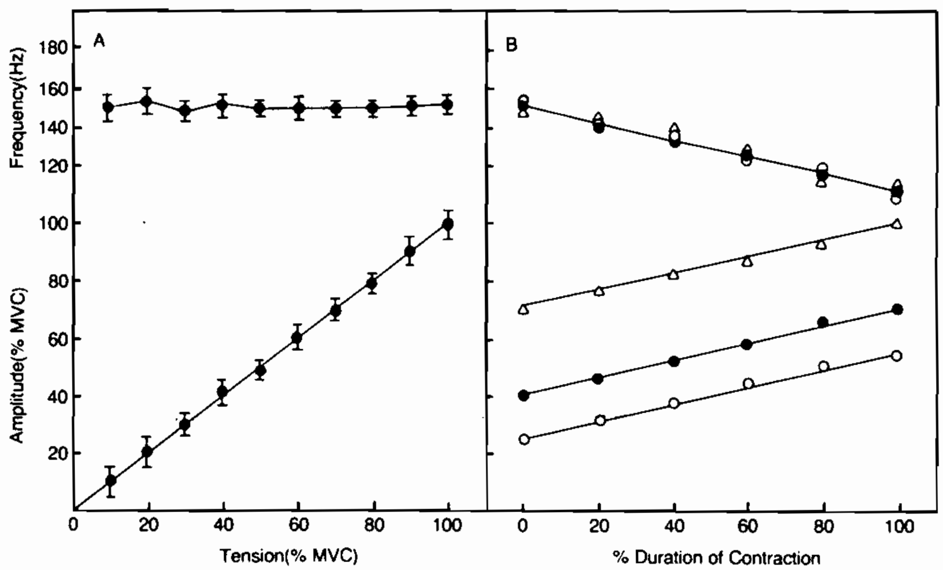

Figure 1. The R.M.S. amplitude and centre frequency of the Fourier power spectra during brief isometric contractions of the handgrip (A) and fatiguing isometric contractions (B) at tensions of 25 (○), 40 (●) and 70% (△) MVC in each of the six subjects.

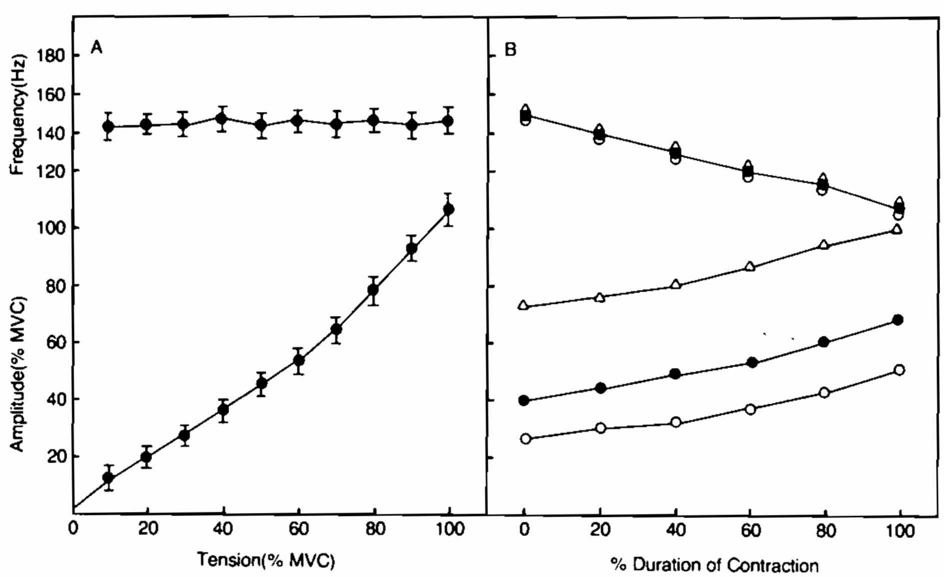

Figure 2. The average R.M.S. amplitude and centre frequency of the Fourier power spectra during brief isometric contractions of biceps muscle (A) and fatiguing isometric contractions (B) at tensions of 25 (○), 40 (●) and 70% (△) MVC in each of the six subjects.

relation between tension and EMG amplitude during brief isometric contractions. Statistical analysis showed that the lowest sum of the residuals for the EMG–tension relationship in the biceps muscle was a second order fit whereas the other three muscles had the lowest sum of the residuals for a first order polynomial fit. The relationship between tension for brief contractions and the centre frequency of the Fourier power spectra appeared to be independent of tension during brief isometric contractions. During the fatiguing isometric contractions in all but the biceps muscle, the amplitude of the EMG rose almost linearly throughout the duration of the contractions at 25, 40 and 70% MVC. Since the amplitude of the EMG rose in parallel for contractions at these tensions, the amplitude of the EMG at the point of fatigue was still related to the tension exerted by the muscles. Therefore, for all three muscles at any point during fatiguing isometric contractions, the amplitude was related to both the tension exerted by the muscle and the degree of fatigue induced in the muscle. Although the same pattern of response was found in the biceps muscle, the EMG amplitude throughout the contractions rose somewhat faster at the end than at the beginning of the contractions. The centre frequency of the Fourier power spectra decreased linearly throughout the fatiguing contractions to the same final value at the end of contractions at any tension that was examined in any of the four muscle groups. There was no significant difference in the pattern of response of the centre frequency of the EMG power spectra since the slopes of the frequency–time graphs were not significantly different.

3.2. *Series 2*

In the second series of experiments, the amplitude and frequency components of the EMG were examined during the brief (figures 3 and 5) and sustained (figures 4 and 6) isometric contractions of the handgrip muscles (figures 3 and 4) and biceps muscle (figures 5 and 6). For all three muscle lengths and in both muscles, although strength varied as a function of muscle length, the amplitude of the surface EMG was directly related to the tension exerted by the muscle during brief isometric contractions. However, the relation between tension and EMG amplitude in the biceps muscle was even more non-linear at the widest elbow angle while being more linear at the narrowest elbow angle. Although the centre frequency was highest at the longest

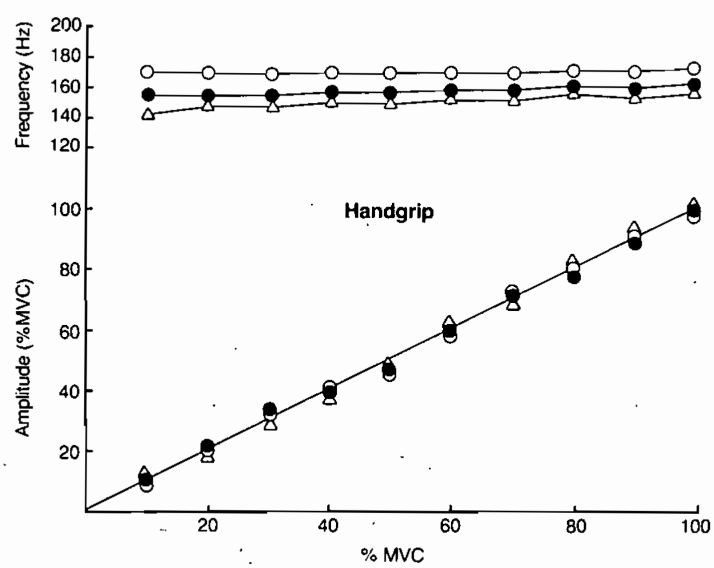

Figure 3. The R.M.S. amplitude and centre frequency of the Fourier power spectra of six subjects recorded during brief isometric contractions in which the handgrip muscles were at (●), above (○) and below (△) optimal length.

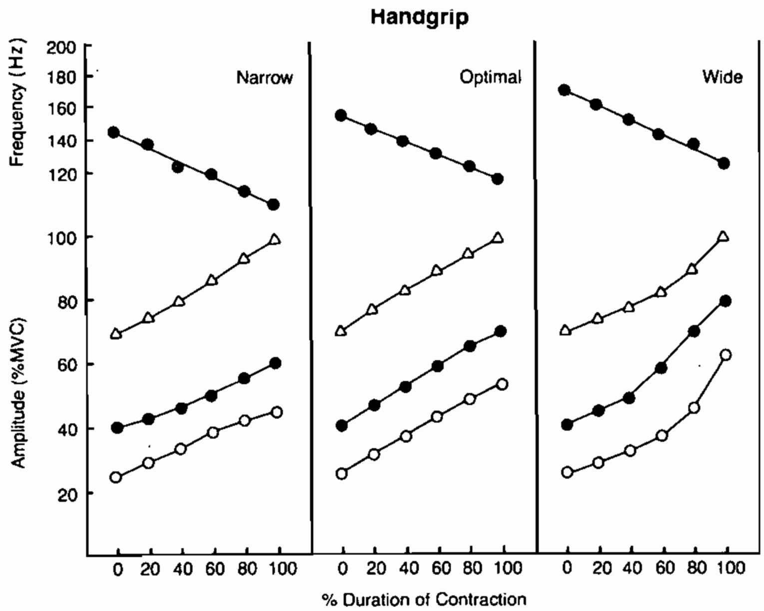

Figure 4. The amplitude and frequency components of the surface electromyogram during fatiguing isometric contractions at 25(○), 40(●) and 70%(△) MVC for the handgrip muscles of six subjects at, above and below optimal length as described in procedures.

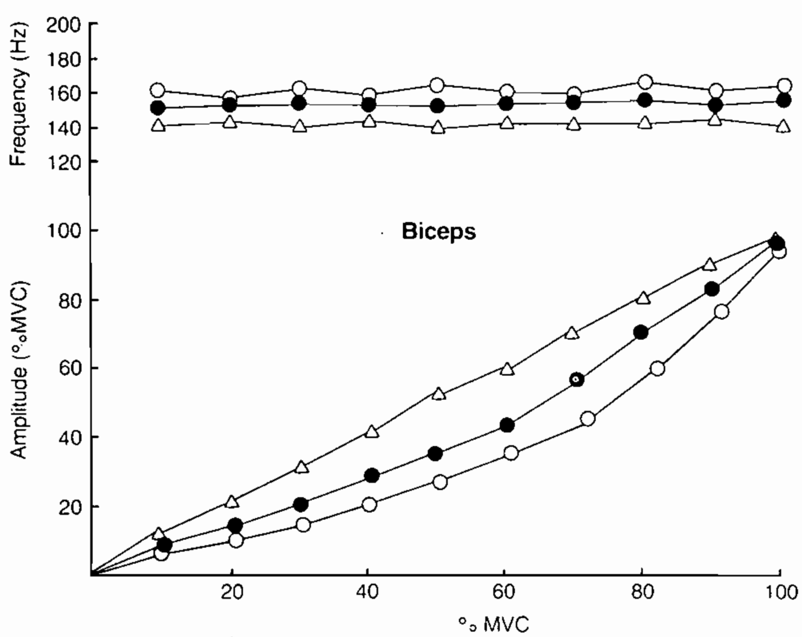

Figure 5. The R.M.S. amplitude and centre frequency of the Fourier power spectra of six subjects recorded during brief isometric contractions in which the biceps muscle was at (●), above (○) and below (△) optimal length.

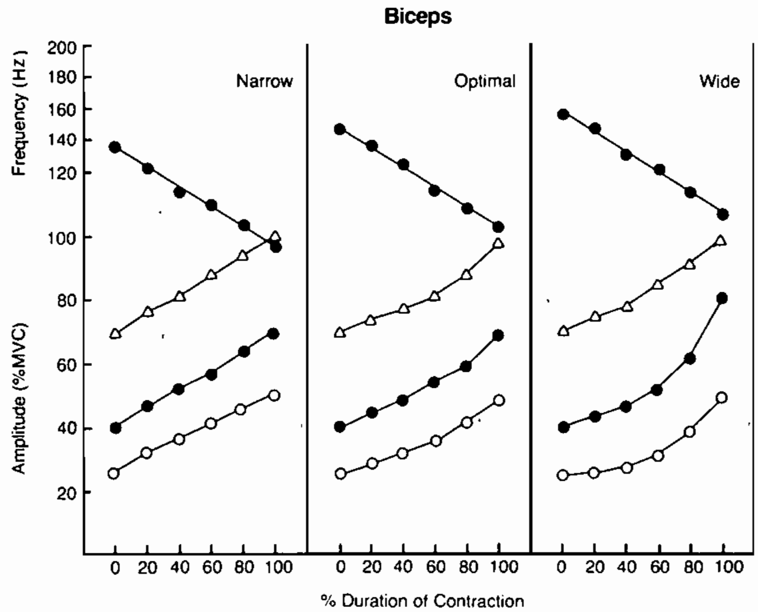

Figure 6. The amplitude and frequency components of the surface electromyogram during fatiguing isometric contractions at 25 (○), 40 (●) and 70% (△) MVC for the biceps of six subjects contracting at, above and below optimal length as described in procedures.

muscle length, the centre frequency appeared to be fairly independent of the tension exerted by the muscles for both muscles and at all muscle lengths. There was no significant difference in the slopes of the EMG frequency-time graphs. During the fatiguing isometric contractions, the amplitude of the EMG rose throughout the duration of the fatiguing contractions in both muscles at any of the three muscle lengths. The centre frequency, which decreased linearly throughout the contractions, was found to decrease by about 25% at any muscle length in both muscles from the beginning to the end of the contractions. The only difference in the centre frequency was the starting and ending frequency which appeared to be a function of muscle length.

4. Discussion

In previous work, it has generally been shown that there is a linear relation between the amplitude of the surface EMG and tension developed by the muscle during brief isometric contractions (Milner-Brown and Stein 1975, Bigland and Lippold 1954, Lind and Petrofsky 1979, Petrofsky *et al.* 1975, 1977, Petrofsky and Lind 1980). During fatiguing isometric contractions, most workers have reported a linear increase in the amplitude of the EMG throughout the duration of contractions (Scherrer and Bourguigon 1959, Eason 1960, Lippold *et al.* 1960, Petrofsky 1981). The centre frequency of the Fourier power spectra of the EMG is considered to be relatively independent of the tension exerted by the muscle during brief isometric contractions Petrofsky *et al.* 1975, Petrofsky and Lind 1980, Viitasalo and Komi 1976) and decreases linearly with time during fatiguing isometric contractions (Petrofsky and Lind 1980, Petrofsky 1980 b). But Zuniga and Simmons (1970) have reported a non-linear relation between the amplitude of the surface EMG and tension during brief isometric contractions and Stulen and DeLuca (1978) have reported a non-linear reduction in the centre frequency with the time during fatiguing isometric contractions. The present investigation shows that for the handgrip muscles, adductor pollicis and quadriceps muscles the response of the EMG to brief and fatiguing isometric contractions were quite similar. For these three muscles there was a linear relation between the amplitude of the EMG and tension for brief isometric contractions and a linear reduction in the centre frequency with time to the same final value at the end of fatiguing isometric contractions. For these muscles then, the centre frequency of the EMG would appear to be a good non-invasive index of muscle fatigue. In contrast, the biceps muscle showed non-linear relation between the amplitude of the EMG and tension for brief isometric contractions while the centre frequency of the EMG still fell linearly during fatiguing isometric contractions. Therefore, even with the same analytical technique, the biceps still showed a different response than did the other three muscles examined here.

There are several possible explanations for the non-linearities between tension and EMG amplitude observed by other investigators and ourselves for this and possibly other muscles. One possibility is that the dynamometer used by some investigators is not truly isometric allowing muscle length to vary throughout the duration of brief and sustained isometric contractions as tension varies due to muscle tremor. Since muscle tension is function of the length of the muscle, this would have the effect of changing the amplitude and frequency components of the EMG.

Another possibility is that the dynamometer did not isolate the muscle group under study adequately. If the dynamometer allowed other muscles to exert force, especially during strong isometric contractions, the recruitment and discharge pattern of the muscles under study would vary causing changes in the EMG amplitude–muscle tension relation.

Electrode placement is another factor which might alter the EMG amplitude–muscle tension relation. Lynn *et al.* (1978) have demonstrated that wide electrode spacing of surface EMG electrodes results in a non-linear relation between the amplitude of the surface EMG and tension for brief isometric contractions. This same relation probably holds true for fatiguing isometric contractions. Thus, it is important to place the electrodes close together and over the belly of the muscle. Since no standardized electrode placement of electrode spacing has ever been established for electromyography, this may also explain some of the variations in EMG analysis recorded in other papers.

In the present investigation, however, electrode placement was constant on the different muscles and the dynamometers were truly isometric, and yet the EMG amplitude–muscle tension relation was still non-linear in the biceps muscle. The reason that this occurs in this one muscle might be due to inherent differences in the muscle itself. Recently, in a brief report, Bigland-Richie *et al.* (1980) showed that the biceps muscle may have a different pattern of motor unit recruitment than the other muscles examined here during brief isometric contractions. Further, the fibre composition of the biceps muscles is different than that of the muscles we examined. The result then of these two factors might be to alter the EMG–tension relation in the muscle during brief isometric contractions as suggested by Bigland-Richie *et al.* (1980) and during fatiguing contractions as well. However, the current investigation does clearly show that the centre frequency of the Fourier power spectra provides a useful fatigue index in at least the muscles examined here. In the present investigation, a small muscle like the adductor pollicis has the same linear decrease in the frequency components of the surface EMG as shown for the handgrip, the biceps and even the quadriceps muscle

(Petrofsky 1979). Since muscle length and muscle mass have no effect on the magnitude of the change in centre frequency of the EMG power spectra in these muscles, it appears that the centre frequency has the potential of being a useful fatigue index. Further investigation with other muscles is warranted.

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Les composantes fréquentielles et l'amplitude de l'électromyogramme (EMG) de surface ont été déterminées pendant 3 s (tensions de 5 à 100% de la contraction volontaire maximum = MVC) et pendant des contractions fatigantes à 25, 40 et 70% de la MVC dans les muscles du poignet, du biceps, du muscle adducteur du pouce et du quadriceps chez six sujets masculins. En ce qui concerne les muscles du poignet et du biceps, les expériences ont été répétées pour trois élongations différentes des muscles: l'élongation pour laquelle le muscle était capable d'exercer sa force isométrique maximale et les élongations au-dessus et en-dessous de celle qui correspond à une élongation pour laquelle le muscle peut exercer une force égale à 80% de son maximum. Les composantes fréquentielles de l'EMG étaient identiques pour les contractions brèves et pour les contractions isométriques fatigantes quels que fussent les mucles considérés, aussi longtemps que la contraction était proche de l'optimum. Le fait de diminuer l'élongation avant les contractions contribuait à augmenter la puissance des basses fréquences dans le spectre de puissance de l'EMG, alors que l'accroissement de l'élongation entraînait un effet opposé pendant les contractions isométriques. Les amplitudes de l'EMG étaient également les mêmes et pour les courtes durées de contraction et pour les contractions fatigantes dans tous les muscles, sauf les biceps. Dans les biceps, on a mis en évidence une relation non-linéaire entre l'amplitude de l'EMG et la tension pendant les contractions isométriques brèves, mais moins nette pendant les contractions fatigantes.

Die Frequenzkomponenten und die Amplitude des Oberflächenelektromyogramms (EMG) wurden sowohl über Abschnitte von drei Sekunden (Anspannung 5–100% der Maximalkraftkontraktion (MVC)) als auch durch ermüdende Kontraktionen von 25, 40 und 70% MVC gemessen, wobei die Handgreif-, Biceps-, Adductor-pollicis- und Quadricepsmuskeln von sechs männlichen Personen untersucht wurden. Für die Handgreif- und Bicepsmusklen wurden die Versuche an drei verschiedenen Muskellängen wiederholt: der Länge maximaler isometrischer Kraftaufbringung sowie oberhalb und unterhalb dieser Länge, entsprechend einer Kraftaufbringung des Muskels von 80% seines Maximums. Die Frequenzkomponenten des EMG waren bei kurzen und bei ermüdenden isometrischen Kontraktionen aller hier untersuchten Muskeln gleich, solange die Muskeln nahe ihrer optimalen Länge kontrahierten. Muskelverkürzungen vor den Kontraktionen bewirkten ein Anwachsen der Leistung in den tiefen Frequenzen des EMG-Leistungsdichtespektrums, während Strecken isometrischer Muskelkontraktion den gegenteiligen Effekt zeigten. Die Amplitude des EMG während kurzer und ermüdender Kontraktionen war für alle Muskeln mit Ausnahme des Biceps gleich. Der Biceps zeigte eine nichtlineare Beziehung zwischen der Amplitude des EMG und der Anspannung während kurzer isometrischer Kontraktionen und zu einem kleineren Betrag bei ermüdenden Kontraktionen.

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