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Surface electromyogram spectral characterization and motor unit activity during voluntary ramp contraction in men

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Summary. The relationships were investigated between the surface electromyographic (SEMG) power spectrum analysed by the 20 order autoregressive model (AR spectrum) and underlying motor unit (MU) activity during isometric contractions increasing linearly from 0% to 80% maximal voluntary contraction. Intramuscular spikes and SEMG signals were recorded simultaneously from biceps brachii muscle; the former were analysed by a computer-aided intramuscular MU spike amplitude-frequency (ISAF) histogram and the latter subjected to AR spectral analysis. Results indicated that there was a positive correlation between the force output and the mean amplitude of the ISAF histogram but not with the mean frequency. These changes were accompanied by changes in relative power of the high frequency (100-200 Hz) peak (HL) in the AR spectrum. It was also found that there was a positive correlation between the mean amplitude of the ISAF histogram and the HL value. These data suggested that the power of the high frequency peak in the AR spectrum of the SEMG signal preferentially reflected the progressive recruitment of underlying MU according to their size. Differences between the AR spectrum and the spectrum estimated by fast Fourier transform algorithm have also been discussed.

Key words: Autoregressive modelling - Motor unit recruitment - Biceps brachii muscle - Surface electromyographic signal - Power spectrum

Introduction

As a result of the remarkable progress of computer technology in the last two decades, power spectral analysis of the surface electromyographic (SEMG) signal has been widely utilized to characterize the frequency property of myoelectric signals related to muscle fatigue (Petrofsky and Lind 1980; Mills 1982), concentration level (Palla and Ash 1981; Hagberg and Ericson 1982; Moritani et al. 1985) and muscle fibre composition (Gerdle et al. 1988). These studies were performed by the fast Fourier transform algorithm (FFT) in which parameters such as mean power frequency and median frequency (MF) were used to characterize the power spectrum density function of the SEMG signal. It was well established that these parameters declined to lower frequency levels during the development of muscle fatigue and that they were closely related to the slowing of conduction velocity of motor unit action potentials (MUAP). However, other important aspects during either fatiguing and non-fatiguing voluntary contraction, such as the relationships between the frequency components of the SEMG signal and the property of underlying motor units (MU), recruitment or rate coding modulation etc., have so far remained unclear.

Recently, parametric representation of myoelectric signals by the autoregressive (AR) modelling of the SEMG signal has attracted considerable attention. In an early study, Brauer et al. (1975) estimated the SEMG power spectrum of brachial muscles by AR modelling (AR spectrum) and showed the difference in spectral components between agonist and antagonist muscles. More recently, Maranzana et al. (1984) have obtained a more reliable power spectrum of a simulated SEMG signal by AR modelling than by FFT spectrum averaged over 48 epochs. Some investigators have also successfully fitted an AR model to an SEMG signal using human subjects (Paiss and Inber 1987; Hefftner et al. 1988; Rosenburg and Seidel 1989).

However, few reports have been concerned with the relationship between AR spectrum of the SEMG signal and underlying MU activities. To test whether the information obtained by the needle EMG test was represented in the SEMG power spectrum, Inber and Noujaim (1984) have compared the AR spectrum of healthy subjects with patients suffering from myopathy and neuropathy. They have concluded that SEMG recordings, when properly processed by AR modelling, could replace needle EMG recordings in some clinical appli-

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cations, although they did not record intramuscular and surface EMG signals simultaneously. Furthermore, the myoelectrical signal was recorded only during steady contraction of 50% maximal voluntary contraction (MVC). Therefore, it is hard to clarify the influence of the various MU activities dependent on exerted force levels on the AR spectrum according to their experimental setting.

In the light of the above advantages of the AR spectrum, it is reasonable to assume that AR modelling of the SEMG signal would make it possible to estimate the underlying MU activity, especially the activity according to the physiologically well-established "size principle" (Henneman 1957) during increasing voluntary contraction. The purpose of the present study was, therefore, to investigate the relationships between some properties of the AR spectrum of the SEMG signal and underlying MU activity during isometric contraction of the biceps brachii muscle with linearly increasing force. To achieve this, we recorded the SEMG signal and intramuscular MU spikes simultaneously under the same physiological conditions.

Method

Subjects. Four male subjects (mean age, body mass, and height, 25.0 (SD 2.4) years, 171 (SD 1.0) cm, 64.5 (SD 4.5) kg, respectively) volunteered to participate in this study, after being informed of the purpose, the possible risk and discomfort associated with the experiments.

The right biceps brachii muscle was tested during an isometric contraction increasing linearly (ramp contraction) from 0% to 80% MVC in approximately 4 s (20% MVC$\cdot$s^{-1}). The MVC was determined by taking the largest of three brief, non-fatiguing maximal isometric efforts; 3-min intervals were allowed between the contractions. During all contractions the subjects were seated comfortably with a fitted leather belt located just below the wrist joint. The subjects kept their right hands in a position midway between pronation and supination. Before any data was collected, all the subjects practised the ramp force output protocol of 20% MVC$\cdot$s^{-1} to reduce the variability in performance. By the end of the practice, all the subjects could almost match the ramp force output to the target force level. The exerted force was transmitted through a load cell (MINEEBA U3B1) and amplified (NEC Sanei) with a low-pass filter at 10 Hz. The subjects were provided with visual feed-back of their force output on a conventional X-Y plotter during all contractions.

Myoelectrical signal recording. The intramuscular spikes of biceps brachii (short head) muscle were recorded by bipolar wire electrodes (100 µm diameter) fixed by a hook. To record the MUAP these electrodes were passed through a 23-gauge, 0.5 inch steel hypodermic needle and inserted into the muscle belly to a depth of approximately 8 mm from the skin surface. The needle was subsequently withdrawn. An ground electrode was attached over the acromion. Consequently the MUAP of the superficial area of the muscle were preferentially detected. No discomfort was experienced from these wire electrodes during testing. The MUAP were then filtered with a high frequency cut-off of 10 kHz.

For SEMG frequency power spectral analysis, bipolar silver/silver chloride electrodes (4 mm pick-up area, 6 mm inter-electrode distance) were applied over the belly of biceps brachii muscle. The SEMG signal was filtered with a low frequency cut-off of 5 Hz and high frequency cut-off of 1 kHz to eliminate aliasing effects on the frequency spectrum analysis.

These myoelectric signals were amplified (NEC Sanei 1253A) and recorded with a force signal on a FM data recorder (Sony A-47). Each record lasted for 4 s and was digitized at a sampling rate of 10 kHz for MUAP, 2 kHz for SEMG signals and 1 kHz for force. The digitized data were sorted within the computer's memory (NEC Sanei 7T18) into eight epochs according to their relative force levels (% MVC), which were then stored on floppy disk for frequency spectrum analysis of the SEMG signal and intramuscular spike amplitude-frequency (ISAF) histogram for MUAP.

Data processing. The analysis procedure of the ISAF histogram and its limitations have been described and discussed in detail elsewhere (Moritani et al. 1985). Briefly, recorded MUAP were isolated by a window-discriminant subroutine and counted according to their amplitude in a predetermined incremental ratio (50 µV) for obtaining the ISAF histograms. For statistical comparison of the ISAF histograms, the mean amplitude and frequency were calculated for each ISAF histogram obtained from each epoch.

The SEMG power spectral analysis was performed by two algorithms, namely the FFT and AR modelling, which have been commonly characterized as non-parametric or parametric estimations, respectively. Firstly, eight epochs of digitized data were processed with the Hamming window function and 512 point FFT to obtain SEMG periodograms (FFT spectrum). Subsequently, the AR model was applied by Levinson-Durbin's algorithm using the autocorrelation function (Bendat and Piersol 1971; Inber and Noujaim 1984; Ito et al. 1985).

In the AR model, each sample $x(n)$ of the SEMG signal is described as a linear combination of the previous samples plus an error term $e(n)$ which is independent of the previous samples. The AR model describes the process $x(n)$ in the following way:

$$x(n) = -\sum_{k=1}^{p} ak \cdot x(n-k) + e(n)$$

where $x(n)$ is the sample of the modelled signal,
ak is the AR coefficient,
$e(n)$ is the residual or error sequence, and
p is the order of the model.

The model can be interpreted as a linear system with $e(n)$ as its input and $x(n)$ its output. The $e(n)$ is the white noise and $x(n)$ is the SEMG signal. The AR spectrum of the sequence $x(n)$ can be estimated from following equation:

$$p_{AR(f)} = \frac{1}{|1 + \sum_{k=1}^{p} ak\, e^{-jwk}|^2}$$

As for the order of the AR model, the value of 20 was selected to characterize the SEMG signal segments according to Inber and Noujaim (1984): they suggested that the order 20 gave a reasonable segment approximation of 0.5 s, taking into account the stationarity of movement of the data (Bendat and Piersol 1971).

As most of the AR spectra revealed mono- or bi-modal characteristics, three spectral parameters were determined to evaluate their shapes quantitatively: first peak frequency (1PF), second peak frequency (2PF), and the "high to low" frequency power ratio (HL) which was the ratio of the first to the second peak power in the AR spectrum. On those occasions where the spectral shape was mono-modal, the latter two parameters (2PF and HL) were impossible to calculate.

Statistics. Statistical analyses were performed using the Student's *t*-test (independent) and simple linear regression analysis. We considered $P < 0.05$ to be significant.

Results

Figure 1 shows typical examples of MUAP and SEMG records during ramp force output at weak (34% MVC), intermediate (51% MVC) and strong (74% MVC) phases of contraction (mean value). Each plot shows the digitized data obtained during 0.512 s. As the force output was increased, the number of large spikes of the MUAP

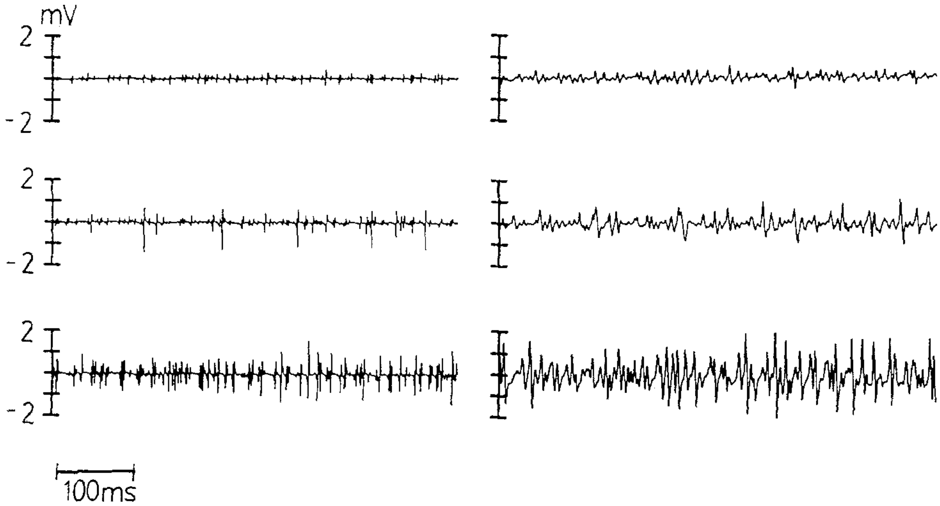

Fig. 1. Simultaneous recording of intramuscular electromyogram (EMG) (*left*) and surface EMG (*right*) during ramp force output. The row from top to bottom show 34%, 51%, 74% maximal voluntary contraction, respectively

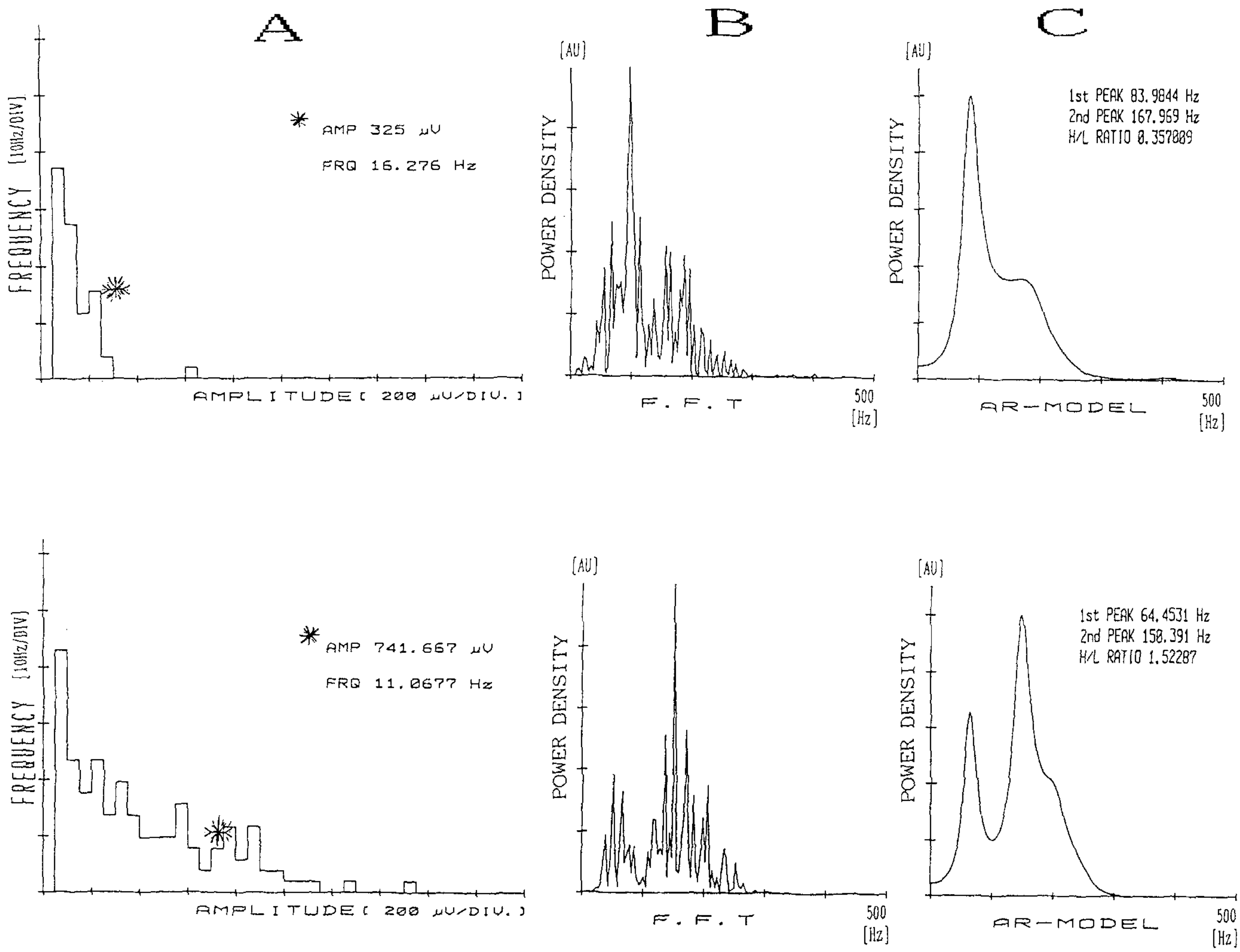

Fig. 2. Changes in intramuscular spike-amplitude (ISAF) histograms (**A**), surface electromyogram power spectra estimated by the fast Fourier transform (*FFT*) (**B**), and that estimated by the autoregressive modelling (AR model) during ramp contraction (**C**). The *upper* and the *lower trace* indicate 34% and 74% maximal voluntary contraction, respectively. The data are from the same subject as in Fig. 1. The asterisks indicate mean spike amplitude and frequency. AU, arbitrary units

and the amplitude of the SEMG signal also increased. However, it was hard to characterize each MUAP activity only by the time domain of the SEMG signal.

Figure 2 shows typical plots obtained from computer processing of the myoelectrical signals of the same subject as in Fig. 1. The rows from top to bottom show relatively weak (34% MVC) and strong (74% MVC) phases of contraction (mean value), respectively.

Column A represents typical ISAF histograms obtained from the intramuscular EMG signal. The asterisks in these plots show both the mean spike amplitude and mean spike frequency of ISAF histograms. A marked increase of the mean amplitude (325 μV to 741 μV) indicated that relatively high amplitude MUAP were included in the EMG recordings during the phase of high force exertion.

Columns B and C represent the FFT spectrum and AR spectrum, respectively. Note that the AR spectrum had a simpler and less oscillatory shape than the FFT spectrum. These characteristics of both spectra were very similar to those of an earlier paper, which also selected the order of 20 to estimate the AR spectrum of the SEMG signal (Inber and Noujaim 1984). Furthermore, the spectral power of the higher frequency band was apparently increased, concomitant with the increase in exerted force levels.

Figure 3 shows the relationships between the parameters determined from ISAF histograms and the levels of force output. Positive correlation ($P<0.01$) was obtained between the mean amplitude of the MUAP and the force levels (Fig. 3A), and a linear relationship was determined. On the other hand, there was no relationship between the mean frequency of the MUAP and the force level (Fig. 3B). Paired t-tests for the group data (0%–40% MVC ($n=14$) vs 40%–80% MVC ($n=18$)) indicated that there were significant increases in the mean amplitude of the ISAF histogram [322.21 (SD 111.25) μV to 664.83 (SD 146.83) μV, $P<0.01$].

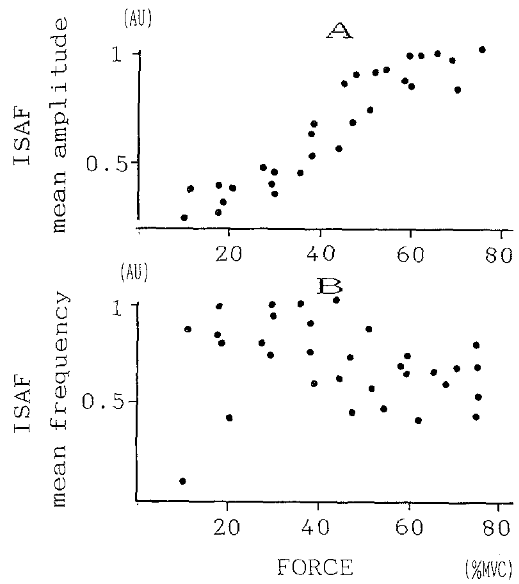

Fig. 3. Relationships between force level (*abscissa*) and mean amplitude (**A**) or mean frequency (**B**) of intramuscular spike amplitude (*ISAF*) histogram (*ordinate*). A significant linear relationship was observed between *ISAF* mean amplitude and force (regression coefficient = 0.94). *MVC*, maximal voluntary concentration; AU, arbitrary units

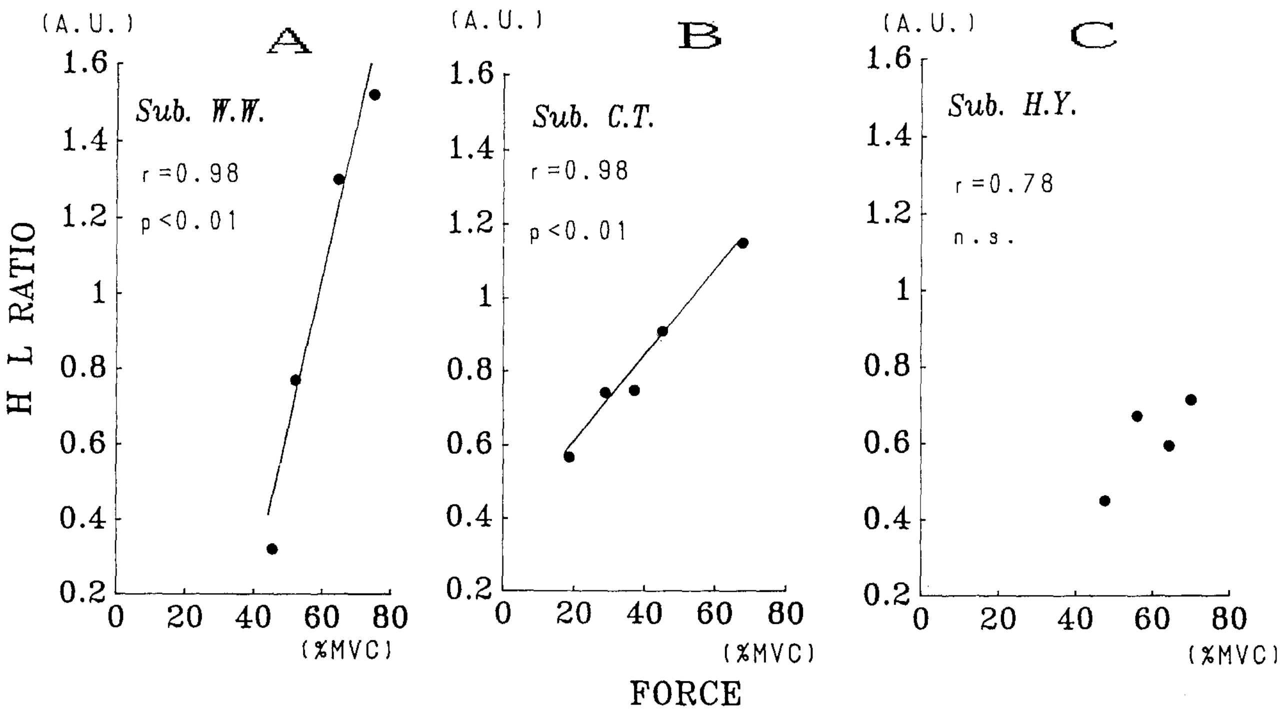

Fig. 4. Relationships between force level (*abscissa*) and "high to low" frequency power ratio (*HL*) of AR spectra (*ordinate*) of three subjects (**A**, **B** and **C**) during ramp force output. Significant linear relationships were observed for two subjects (regression coefficients >0.95). Other definitions as in Figs. 2 and 3

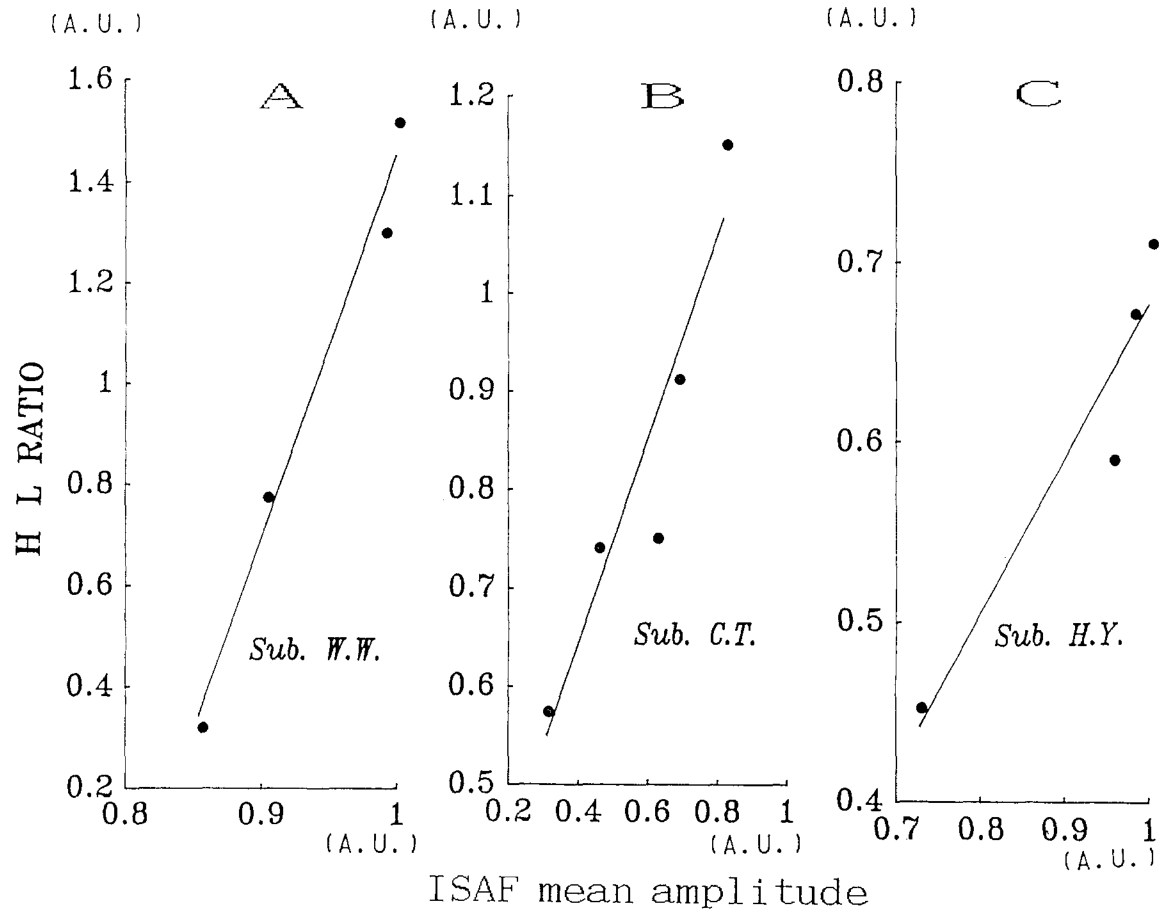

Fig. 5. Relationships between *ISAF* mean amplitude (*abscissa*) and *HL* (*ordinate*) of three subjects (**A**, **B** and **C**). Significant linear relationships were observed (regression coefficients >0.93) for all subjects. For definitions see Figs. 2 and 4

Figure 4 shows the relationships between the HL calculated from the AR spectrum and the exerted force levels. Although we have selected the fixed AR order of 20, the spectral shapes obtained were too varied to enable quantification by previously determined spectral parameters. Therefore, we established three criteria to discriminate the AR spectrum that could be subjected to statistical analysis. Firstly, spectral waveform should have bi-modal characteristics. Secondly, the HL should be more than 0.3. Thirdly, the 2PF should be within 200 Hz.

The HL of the AR spectra selected by these criteria are plotted in Fig. 4 according to subject (A, B, and C). We excluded the AR spectra of the fourth subject from the present statistical analysis because all the AR spectra obtained were mono-modal. These differences might be due to a statistical property of the signals (Ito et al. 1985) and a higher order of AR model would have been necessary to obtain bi-peak spectrum in respect of this subject.

Linear relationships between HL and force levels were obtained from two of the three subjects (A and B, $P<0.01$). However, it was seen that the changes in 1PF and 2PF were not dependent on the exerted force level.

Figure 5 shows the relationship between HL and the mean amplitude of ISAF histograms. There was a positive correlation between HL and the mean amplitude of MUAP in all subjects ($P<0.01$ for A and $P<0.05$ for B, C).

Discussion

MU activity during incremental force output

The present experimental evidence on human voluntary contraction, especially isometric contraction, strongly supports the "size principle" derived from animal experiments by Henneman (1957) which showed that recruitment and firing properties, contractile force, metabolic pattern, fatigability (Milner-Brown et al. 1973; Freund et al. 1975; Goldberg and Derfler 1977; Monster 1979) and muscle fibre conduction velocity (Andreassen and Arendt-Nielsen 1987) of MU are determined by their size. The present finding of a significant increase of the mean amplitude of MUAP and its highly significant correlation to exerted force levels ($r=0.94$, $P<0.01$) also provide some evidence that newly recruited MU which have relatively large amplitudes are involved in ramp force output (Fig. 3A). By measuring the spike amplitude and recruitment threshold of single MU, Goldberg and Derfler (1977) have also shown a relatively high correlation coefficient

($r = 0.78$) between these two parameters. However, we calculated the mean amplitude of MUAP and the exerted force levels from the pooled data of 0.512 s. Therefore, in the strict sense, these two results are of a different nature. Nevertheless, the mean amplitude of MUAP reflected, at least, the dominant spike amplitude of already active or newly recruited MU in a range of exerted force levels. Therefore, the increase of the mean amplitude of MUAP did indicate the orderly recruitment of individual MU.

On the other hand, Johnson et al. (1973) have indicated that as a result of investigating autopsy subjects they found the superficial area of biceps brachii muscle contained a higher proportion of type II fibres than the deep area. Furthermore, Polgar et al. (1973) showed that the size of type II fibres was significantly larger than that of type I fibres in the superficial area of the biceps brachii muscle; whereas no significant differences in size were found in the deep area.

According to these investigations, it was clear that the distribution of the muscle fibre, either in type or size, was not random in the biceps brachii muscle. Consequently, the MUAP detected may be quite different depending on the depth of the indwelling electrode. We inserted the wire electrodes into the superficial area of the biceps brachii muscle; a relatively large number of type II fibres should, therefore, have been involved during the ramp contraction, especially during strong contractions. It follows that a significant increase of the mean amplitude of MUAP indicated the recruitment of larger number of type II fibres located in the surface area of the muscle and with relatively large diameters, depending on the level of the contraction force.

However, no significant relationships could be detected between changes in mean spike frequency of MUAP and the exerted force. Because activities of several MU (already active or newly recruited) was analysed in a ISAF histogram, it was not appropriate to suggest that the mean frequency of the ISAF histogram reflected the firing rate of individual MU immediately. Whereas these results seemed to be consistent with the observation that the most common pattern of the MU in the biceps brachii muscle was a constant or *slightly* increasing instantaneous firing rate during ramp contraction, some units showed, however, a decline in instantaneous firing rate as force increased (Denier van der gon et al. 1985). In any case, it was not likely that the mean frequency of the ISAF histogram increased depending on the exerted force level as observed in the mean amplitude, because various types (but not a considerable increase) of firing behaviour were observed in MU of human biceps brachii muscle during ramp contraction. Moreover, Kukulka and Clamann (1981) have suggested that recruitment played a more important role throughout the contractile force range in biceps brachii muscle but rate coding was more important in adductor pollicis muscle. DeLuca et al. (1982) have also indicated that these muscle dependent activities of MU were very important for "smooth force output", such as the ramp force output of the present investigation.

Therefore, we concluded that in our present study the predominant parts of the incremental force output originated from the orderly recruitment, rather than firing rate modulation, of larger and faster conducting MU situated in the surface areas of biceps brachii muscle.

Characteristics of AR spectrum of SEMG signal

The most obvious characteristic of AR spectrum was its simplicity, as shown clearly if one compares the AR spectrum with the oscillatory FFT spectrum (Fig. 2B, C). Simplicity is one of the properties of the spectra estimated by the linear prediction model (Ito et al. 1985). This property enabled us to recognize the characteristics of SEMG spectral shape more easily.

To obtain such a simple spectrum of the SEMG signal, many investigators have used the averaging method of several FFT spectra. For example, FFT spectra of 20 epochs (Moritani et al. 1986) or 48 epochs (Palla and Ash 1981) have been averaged. However, Maranzana et al. (1984) have shown that the AR modelling of a single epoch produced a similar spectrum to that obtained by averaging 48 temporal epochs of FFT spectra. They have also suggested that it was possible to replace the use of the FFT algorithm, which required the averaging of many periodograms for reliable estimates, with the AR spectrum.

In recording the SEMG signal, especially when a strong Contraction nearly up to MVC is performed, it is very difficult to maintain all the physiological or electrical conditions in the same state (e.g. muscle temperature, blood flow, etc.) for as long as is necessary to obtain enough epochs for averaging. So, AR modelling may be a very useful tool to obtain a smooth spectrum with the minimum of artefacts arising from the alteration of detecting conditions, which is a critical factor in spectral analysis.

Force dependent changes of AR spectrum and their relationship to MU activity

The principal observation was that HL of AR spectrum strongly reflected the underlying MU recruitment strategy of biceps brachii muscle according to the size principle during incremental force output (Figs. 2, 5).

These findings seem to be significant for the following reasons. Firstly, to our knowledge there are few data that successfully quantify the SEMG signal taking the various shapes of the spectra into account. Until now, some investigators have attempted to quantify frequency band-specific characteristics of SEMG spectrum to obtain similar or more detailed information than the algebraic mean value. For example high to low ratio parameters have been used, i.e. the ratio of total power between the low frequency components and high frequency components of an FFT spectrum (Bigland-Ritchie et al. 1981; Moxham et al. 1982). However, the values of these separation points seem to lack objectivity with respect to the spectral shape. Usually, the FFT spectrum is in the form of an oscillatory and highly varied shape unless enough epochs are averaged. Since it is hard to delineate the unbiased separate frequency from the characteristics of the spectral shape, many investigators have been obliged to determine this criterion from experience.

On the other hand, the AR spectrum of 20-order has the obvious mono- or bi-modal characteristics, because of its simplicity (Fig. 2C). Therefore, it is very easy to distinguish objectively between 1PF and 2PF without any artificial criteria separating the spectrum into low and high frequency bands. Paiss and Inber (1987) have also shown frequency band-specific characteristics of AR spectrum. They have demonstrated that the low frequency peak of SEMG frequency spectrum could be detected by 30-order AR modelling. On the other hand our findings suggest that high frequency components can also be characterized by means of 20-order AR spectrum.

Secondly, the HL of the AR spectrum strongly reflects the amplitude of the underlying MU during incremental contraction. Many investigators have shown that there is a linear relationship between threshold force, twitch force, and the amplitude of MU (Milner-Brown et al. 1973; Goldberg and Derfler 1977). More recently, Andreassen and Arendt-Nielsen (1987) have shown that the conduction velocity of MU in human anterior tibial muscle correlated with twitch torque. According to this evidence, we consider that high threshold (maybe high twitch torque and amplitude) MU should have relatively high frequency components (short conduction velocity) and, therefore, should preferentially affect the high frequency band of the SEMG frequency spectrum.

De Luca (1984) has mentioned that some physical properties act as a filter to the SEMG signal before it can be observed. Muscle tissue, for example, acts as a low-pass filter because the tissue around the active fibre has the function of a volume conductor (Lindstrom and Petersen 1983). However, the HL in the present investigation were shown to be dependent on the amplitude of the underlying MU in spite of these filtering effects; we believe these effects may have been minimal in our experimental setup because we detected the MUAP from superficial areas of the muscle belly. Furthermore, we had selected an electrode of smaller diameter and shorter interelectrode distances than in earlier studies (Petrofsky and Lind 1980; Palla and Ash 1981) to avoid the filtering effect arising from electrode configurations (Basmajian and De Luca 1985). These recording conditions enabled us to reduce the extent of the pickup area. The small pick-up area in turn enabled us to diminish the myoelectrical signals from deeper areas of muscle which are affected by much of the muscle tissue filtering effect (Basmajian and De Luca 1985). Therefore, the low-pass filtering effect of the tissue may not have affected the HL of the AR spectrum quite so much.

Consequently, our data were consistent with the idea that the HL value of the AR spectrum preferentially reflected the waveform of MUAP, especially that of high threshold MU located in superficial areas of biceps brachii muscle. These results have been supported by clinical experiments which have indicated that AR spectrum retain enough global information about the shape of MUAP (Inber and Noujaim 1984).

Thirdly, we have demonstrated clear relationships between the force level and SEMG frequency parameters of the AR spectrum. Until now, there have been some contradictions about the relationship between exerted force levels and frequency parameters of the FFT spectrum. For example, it has been shown that the increase in force level was associated with a spectral parameter shift to lower frequencies (Palla and Ash 1981), that changes of frequency were independent of the force level (Petrofsky and Lind 1980), that frequency change was dependent on an increase in contraction force up to 30% MVC and thereafter became independent (Hagberg and Ericson 1982), and that the frequency change was linearly dependent on exerted force up to 80% MVC during ramp contraction (Moritani and Muro 1987).

These inconsistent results may be caused by the filtering effect of muscle tissue and electrode configurations, the size of the innervation zone of each MU (DeLuca 1984), the differences in muscle fibre types (Westbury and Shanghnessy 1987; Gerdle et al. 1988), or the difference in recruitment or firing strategy (Kukulka and Clamann 1981; DeLuca et al. 1982).

However, our data suggested that even during contractions exerting high tension, the power of the high frequency band of the AR spectrum was linearly related to the force levels. Recently, Solomonow et al. (1990) have indicated that orderly recruitment of MU gave rise to an increase in MF of the intramuscular EMG signal, whereas a change in the firing rate had very little effect. They have also suggested that if the filtering effect of tissue and electrode configuration were considered, it was possible to extend their findings to the SEMG signal. Our data clearly indicated the orderly recruitment of MU in the biceps brachii muscle, which meant that the exerted tension was mainly by the recruitment strategy of MU (Kukulka and Clamann 1981). Therefore, the HL of the AR spectrum reflected the MU recruitment strategy depending on the force levels up to 80% MVC, according to our experimental set up.

In summary, the present data suggested that the HL of the AR spectrum of the SEMG signal preferentially reflected the progressive recruitment of underlying MU. In view of the above discussion, this technique may also be useful in "non-invasive" prediction of the proportion of fibre type (Wretling et al. 1987), in SEMG spectral analyses of fast ramp or ballistic contraction (Desmedt 1981), and in cases where EMG recording, using needle electrodes is difficult to perform, such as the study of children (Lindstrom and Malmstron 1983). It obvious, however, that further evaluation of this technique is needed.

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