EMG power spectrum as a measure of muscular fatigue at different levels of contraction

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Abstract—*The shift in the power spectrum resulting from a 5–7 min fatigue-inducing effort followed by a 1–2 min recovery period of two elbow flexors, the biceps brachii (BB) and the brachio-radialis (BR), was assessed using two variables, the mean frequency* F_m *and the median or central frequency* F_{md}*. These two variables were calculated in pre- and post-fatigue conditions and following a brief recovery, at four levels, namely 20, 40, 60 and 80 per cent of maximum voluntary contraction (MVC). These were taken from a ramped isometric effort that is from 0 to 100 per cent MVC. The EMG activity of the two flexors was recorded with bipolar surface electrodes from a group of ten volunteers. Following muscle fatigue, induced with a maintained 60 per cent MVC isometric contraction, a statistically significant* ($p < 0{\cdot}05$) *shift towards the lower frequencies was observed for both* F_m *and* F_{md} *for both muscles. Following a brief recovery, a shift towards the pre-fatigue higher frequencies was statistically significant* ($p < 0{\cdot}05$)*. These two synergists responded to muscle fatigue and recovery similarly, as they both demonstrated parallel shifts in power spectrum. The power spectrum is consequently a reliable measure of muscular fatigue. It is also complementary to the net articular moment results.*

Keywords—*Electromyography, Muscular fatigue, Power spectrum*

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1 Introduction

THE ELECTROMYOGRAPHIC (EMG) signal has been used to study muscular fatigue. For example, the temporal characteristics of this signal have been suggested to be a sensitive measure of muscular fatigue (DE VRIES, 1968; CURRIER, 1969; MORITANI *et al.*, 1982; MILNER-BROWN and MILLER, 1986; MILNER-BROWN *et al.*, 1986). The EMG/moment relationship has also been suggested to be an index of fatigue (LENMAN, 1959; MULDER and HULSTIJN, 1984) but our recent experiments have demonstrated a low level of reliability of this index (SMYTH *et al.*, 1990).

The frequency characteristics of the EMG signal have also been presented as a potential measure of muscular fatigue. For example, it has been shown that for different muscles, there is a shift of the power spectrum towards the lower frequencies with fatigue relative to pre-fatigue (LLOYD, 1971; PETROFSKY *et al.*, 1982; DELUCA, 1983). Moreover, it has been demonstrated that the higher the content of fast twitch fibres (FT) in a given muscle, the more this shift is apparent following muscular fatigue (KOMI and TESCH, 1979; MORITANI *et al.*, 1982). This shift has also been demonstrated to be highly correlated with a decrease in the conduction velocity of the muscle tissue (EBERSTEIN and BEATTIE, 1985; MILNER-BROWN and MILLER, 1986), even though contrary evidence has been presented on this issue (NAEIJI and ZORN, 1982).

It is accepted that FT fibres are selectively affected by a fatigue state. These fibres possess characteristics of high tension production and high conduction velocities (see SYPERT and MUNSON, 1981, for a review). They are furthermore recruited after the slow twitch (ST) and the fatigue-resistant fast twitch (FRFT) fibres according to the size principle (HENNEMAN, 1981) of muscular recruitment. Thus, it is believed that the disappearance of these FT fibres with fatigue might be related to the reported shift in the power spectrum.

Muscles of well trained subjects, having a high content of FT fibres, show a clearer shift in the power spectrum than the same muscles of subjects with a lower FT fibre content (KOMI and TESCH, 1979). Also, muscles with higher content of FT fibres show clearer shifts in the power spectrum than other muscles of the same subject with fewer FT fibres (OCHS *et al.*, 1977). These two types of observations might well be a good indication that the EMG power spectrum is, either directly or indirectly, sensitive to the fatiguing of these FT fibres. If one were to study a given muscle with a known percentage of fibre types, one would expect that at low levels of force production the expected shift found in post-fatigue would not be apparent because only ST fibres would be recruited. However, at higher levels of force production, the post-fatigue shift should be

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apparent because the affected FT fibres would be involved.

The aim of the present study is to verify if significant differences exist in the EMG power spectrum between pre- and post-fatigue states, at different levels of maximum voluntary contraction (MVC) produced by elbow flexors. As only one level (percentage) of this MVC has usually been reported in the literature, it is believed that the present investigation could contribute to the study of the sensitivity of the power spectrum shift.

2 Methodology

Ten subjects, five males and five females, aged 25–40 years, volunteered to participate in this study. The experimental protocol used is described in an accompanying communication (SMYTH *et al.*, 1990). The following is a brief summary of this protocol. The subjects were comfortably restrained with a belt to a chair. An isokinetic dynamometer (Cybex II, Lumex Corp.) was positioned, allowing measurement of an isometric forearm flexor moment, such that the arm and forearm formed a 90° angle at the elbow. The hand was maintained voluntarily in a mid-pronation/mid-supination position and the back of the elbow rested against a foam pad.

Five pairs of miniature surface electrodes (Beckman) were placed longitudinally to the muscle fibres over the muscle belly of the biceps brachii (BB), the brachio-radialis (BR), the anterior portion of the deltoid (DA), the triceps brachii (TB) and the anconeus (SU). Each pair of electrodes had an interelectrode distance of approximately 10 mm. The EMG signals were amplified by preamplifiers and amplifiers (Teca, Series MK-111) and filtered with lower and upper cutoff frequencies of 16 Hz and 800 Hz, respectively. The BB and BR were considered to be the two main agonists of elbow flexion. JOHNSON *et al.* (1973) have shown that the BB has a content of 42·3 per cent ($\pm$8·0 per cent, $N = 6$) ST-type fibres at its surface and 50·6 per cent ($\pm$9·7 per cent, $N = 6$) of the ST at deeper parts of the muscle, whereas the BR contains 39·8 per cent ($\pm$12·2 per cent, $N = 6$) ST-type fibres. There thus seems to be a trend: the BB muscle presenting more ST fibres than the BR muscle. Overall results were only reported regarding the BR muscle fibre typing.

An initial adjustment period was used permitting the subjects to practise performing an isometric, ramped contraction ranging from 0–100 per cent MVC. A period of 5 s was allotted to produce this contraction. An oscilloscope (Tektronix) was positioned to give visual feedback of the moments registered by the dynamometer to the subjects. The experimenter had a visual feedback system (Nihon-Khoden monitor) for the EMG and moment signals. Once familiar with the procedures, recordings of 8 s were made for each of six ramped contractions. An analogue-to-digital conversion of these data was performed at a sampling rate of 1000 Hz, using a PDP-11/23+ (Digital Equipment Corp.) computer.

The six required contractions were obtained as follows. Three pre-fatigue contractions were recorded, each contraction being separated by a 1 min resting period. Then, local muscle fatigue was induced with a 60 per cent MVC isometric contraction of the elbow flexors, maintained to exhaustion, i.e. for a 5–7 min period. Immediately following this effort, three post-fatigue contractions were recorded, each contraction being separated by a 1 min resting period.

The EMG power spectra were determined at four levels. 20, 40, 60 and 80 per cent of MVC, for each of the contractions recorded. The calculations were made on 0·512 s of EMG recordings with the fast Fourier transform (LSP-11, Digital Equipment Corp.) software package. Each spectrum obtained was filtered using a moving-average approach for the purpose of representation. Recordings of the EMGs were not considered at the 100 per cent MVC because too high a level of EMG variability has been reported at this level (YANG and WINTER, 1983).

Plots of the frequency spectrum for the BB and BR at 20, 40, 60 and 80 per cent MVC were obtained. Also, the mean power frequency F_m and the median or central frequency F_{md} for the two elbow flexors at the same percentages of MVC were also calculated. Of the six contractions recorded, only three were selected for further analysis. One of the three pre-fatigue contractions was chosen to represent the pre-fatigue condition (pre). The first contraction following the muscle fatigue effort represented the post-fatigue condition (post) and the final contraction was chosen to reflect the recovery condition (rec) (Fig. 1). The selection of the pre-fatigue contraction was based on the criterion that the shape of its moment/time curve (0–100 per cent MVC) be most similar to the moment/time curve of the post-fatigue condition.

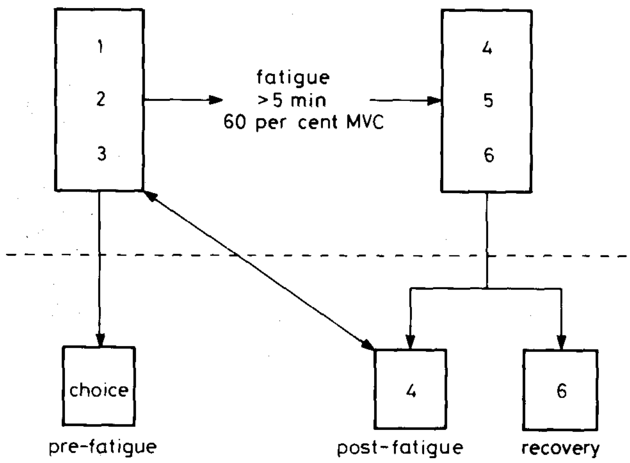

Fig. 1 *Representation of the selection procedure used for the three conditions being contrasted. See text for description*

One-way analyses of variance (ANOVAS) with repeated measures were performed on the F_m and the F_{md} at 20, 40, 60 and 80 per cent MVC for both BB and BR, across the three conditions studied, i.e. pre-fatigue, post-fatigue and recovery (MYERS, 1972). The level of significance was set at $\alpha = 0{\cdot}05$.

3 Results

A visual representation of a set of the power spectra obtained for the BB and BR of one representative subject is provided in Fig. 2. The power content of each spectrum increases with an increase in the percentage of MVC within each separate graph. A slight shift is observed in the post-fatigue compared with the pre-fatigue state (Fig. 3) for the BB muscle. A similar shift in the spectra was also obtained for the BR. There tended to be no major individual differences between the ten subjects.

The numerical data contained within Table 1 include the average F_m and F_{md} (with SD) values of the ten subjects calculated at 20, 40, 60 and 80 per cent MVC for the BB. Table 2 presents the same results for the BR muscle. Without exception, consistent shifts in the average F_m and F_{md} values were obtained. A shift towards the lower frequencies, with differences ranging from 6·8 Hz to 31·0 Hz was evident following the bout of muscle fatigue. With a brief recovery period following fatigue, average shifts ranging from 3·5 Hz to 12·6 Hz, back towards the initially higher pre-fatigue frequencies were found to occur.

Tables 3 and 4 give the results of the one-way ANOVAS with repeated measurements conducted to determine whether the observed shifts in the F_m and F_{md} were statistically significant ($p < 0{\cdot}05$) for the BB and the BR, respectively. Significant differences were found for all the values of the power spectra calculated, except at a low level of contraction (20 per cent MVC) only for the F_{md} variable. There was a statistically significant difference (ANOVA for repeated measurements, $p < 0{\cdot}01$) in the maximum moment values obtained (SMYTH *et al.*, 1990), across the three measures taken, indicating the presence of muscular fatigue.

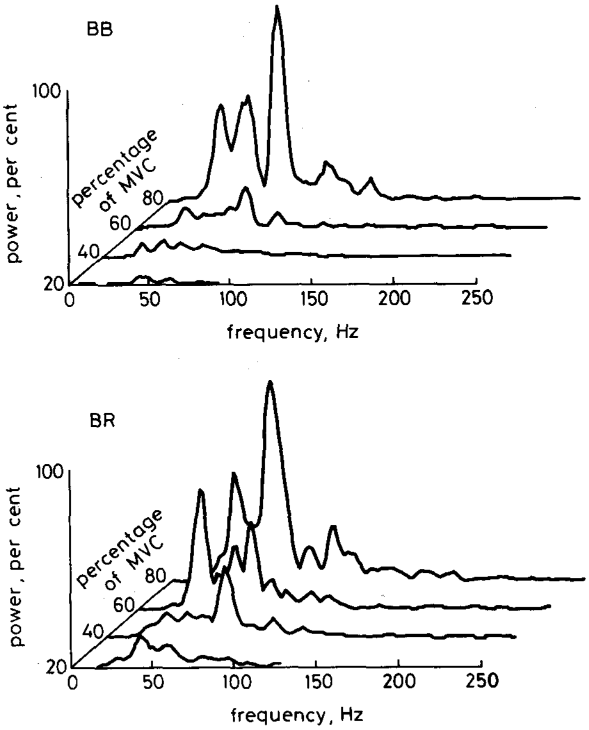

Fig. 2 *Power spectra obtained for the biceps brachii (BB) and brachio-radialis (BR) of one representative subject, at different levels of maximum voluntary contraction (MVC)*

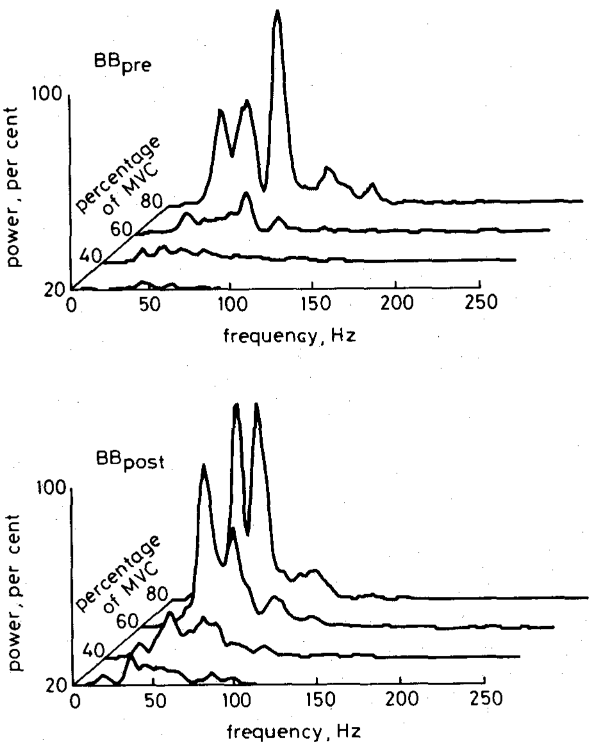

Fig. 3 *Comparison of the pre/post-fatigue states for the biceps brachii (BB) muscle of one subject, at different levels of maximum voluntary contraction (MVC)*

4 Discussion

The results of the ANOVAS (Tables 3 and 4) indicate that, along with the presence of statistically significant decreases in the joint moment produced (SMYTH *et al.*, 1990), there

Table 1 Descriptive statistics of the mean power frequency F_m and median frequency F_{md} of the biceps brachii (BB) power spectra results obtained at different levels of maximum voluntary contraction (MVC) across repeated measurements pre, post and rec)

Percentage of MVC		F_{md} Pre	F_{md} Post	F_{md} Rec	F_m Pre	F_m Post	F_m Rec
20	$\bar{X}$	78·7	71·9	75·4	92·8	82·1	87·2
	SD	18·6	13·4	16·4	19·4	17·0	17·5
40	$\bar{X}$	87·9	71·7	80·3	100·0	82·3	91·7
	SD	15·6	15·4	15·5	18·8	19·0	17·3
60	$\bar{X}$	86·1	70·9	83·2	96·7	83·2	94·1
	SD	23·5	16·9	18·4	23·8	19·4	20·3
80	$\bar{X}$	84·8	67·8	77·5	99·1	78·8	88·8
	SD	21·3	18·5	23·0	24·8	21·8	21·5

Table 2 Descriptive statistics of the mean power frequency F_m and median frequency F_{md} of the brachio-radialis (BR) power spectra results obtained at different levels of maximum voluntary contraction (MVC) across repeated measurements (pre, post and rec)

Percentage of MVC		F_{md} Pre	F_{md} Post	F_{md} Rec	F_m Pre	F_m Post	F_m Rec
20	$\bar{X}$	92·4	85·6	92·4	107·1	96·9	104·1
	SD	23·6	15·3	20·8	21·6	16·1	19·1
40	$\bar{X}$	101·6	86·5	96·1	115·8	99·6	109·4
	SD	22·0	18·9	21·4	21·7	19·2	18·7
60	$\bar{X}$	106·3	81·1	93·7	119·5	95·7	107·9
	SD	30·5	16·7	19·6	26·0	18·8	19·3
80	$\bar{X}$	106·2	75·2	85·0	120·6	89·9	100·0
	SD	30·8	18·9	21·0	25·4	20·3	18·6

Table 3 Results of the ANOVAS performed on the mean power frequency F_m and median frequency F_{md} results for the biceps brachii (BB) power spectra obtained at different levels of maximum voluntary contraction (MVC)

Percentage of MVC	F_{md} F	F_{md} $p<$	F_{md} R^2	F_m F	F_m $p<$	F_m R^2
20	1·3	NS	0·03	3·8	0·05	0·06
40	9·3	0·01	0·16	11·8	0·01	0·13
60	6·7	0·01	0·10	5·8	0·05	0·07
80	6·5	0·01	0·10	9·8	0·01	0·12

F = F-value obtained (ANOVA)
p refers to the level of significance (α)
R^2 = coefficient of determination

Table 4 Results of the ANOVAS performed on the mean power frequency F_m and median frequency F_{md} results for the branchio-radialis (BR) power spectra obtained at different levels of maximum voluntary contraction (MVC)

Percentage of MVC	F_{md} F	F_{md} $p<$	F_{md} R^2	F_m F	F_m $p<$	F_m R^2
20	2·0	NS	0·02	5·6	0·05	0·05
40	10·9	0·01	0·08	11·0	0·01	0·10
60	11·5	0·01	0·17	15·2	0·01	0·17
80	13·4	0·01	0·22	18·5	0·01	0·26

F = F-value obtained (ANOVA)
p refers to the level of significance (α)
R^2 = coefficient of determination

are significant decreases in most of the spectra obtained for the two muscles investigated. These differences are found across the three measurements taken in time. However, the F_{md} of the spectra obtained at 20 per cent MVC did not reach a significant level. Starting at 40 per cent MVC, it appears that the shift in the spectra observed towards the lower frequencies is a consistent finding.

This latter point is of interest because we have found (SMYTH *et al.*, 1990) that in post-fatigue, at the 40 per cent MVC level, a saturation of the EMG signal started to occur for both BB and BR in about 60 per cent of the subjects. It had consequently been suggested that in these cases, at this level, all the motor units (MUs) had been recruited and were firing at about their highest possible rates. Because there is evidence that at that level most of the MUs are recruited, the FT fibres would also have been accessed. As the FT fibres are more affected by the fatigue state, the statistically significant shift should become apparent at this 40 per cent MVC level, as is presently the case. It can also be observed from Tables 3 and 4 that across the percentage MVC levels, the coefficient of determination (R^2) values tend to increase, depicting the fact that a more important difference exists across the three repeated measures for a given analysis. This coefficient represents the percentage of the total variance that explains the treatment effect. Most of the remaining variation in the data reflects the between-subject differences.

The fact, also, that the F_{md} is less sensitive than the F_m in detecting differences in the obtained power spectra is of interest. This illustrates the fact that this statistic, F_{md}, is more conservative than the F_m. The latter, however, is affected by extreme values of the distribution of scores composing the spectrum and would tend to reflect changes that are occurring even at low levels of percentage MVC. The F_{md}, by not reflecting such differences, indicates that, even if the distribution of scores has presented some changes, such as an increase in its SD, its centre or median value has not changed. In the existing literature, however, authors use only one or the other of these statistics, very often without justification, even if the median has been suggested as being a more reliable estimator of the power spectrum (STULEN and DELUCA 1981; MERLETTI *et al.*, 1985). If the two variables were currently reported, it is expected that similar results would most probably have occurred.

Finally, it is believed that the use of smaller electrodes and a smaller interelectrodes distance would have resulted in possibly sharper pre/post-fatigue differences. It has recently been suggested by MORITANI and MURO (1987) that a 6 mm interelectrode distance offers power spectrum data that are correlated with the moment data (see also MURO *et al.*, 1982). This would indicate that the power spectrum would be sensitive to the type of MUs recruited, a hypothesis which remains to be validated.

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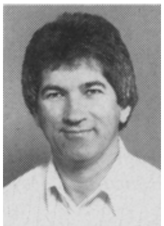
Susan Nagata was born in Toronto, Canada. She received a B.Sc. (Human Kinetics) degree from the University of Guelph in 1982 and an M.Sc. in Health Science (Rehabilitation) from the School of Physical & Occupational Therapy, McGill University, in 1984. Her studies continued in biomechanics at the doctoral level at the Université de Montréal with financial assistance from the Institut de Recherche en Santé et Sécurité de Travail du Québec.



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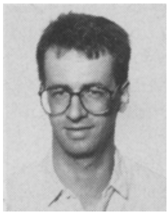
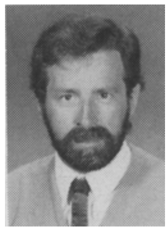
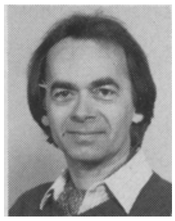


Denis Gagnon earned a B.Sc. in Physical Education (1980) and an M.Sc. in Kinanthropology (1985) at the Université de Sherbrooke. He is a Ph.D. student in Biomechanics at the Université de Montréal, where he is performing research on muscular co-contraction and fatigue and also on tridimensional quantification of human body motion. He is a faculty member of the Ecole de l'Activité Physique, Université Laurentienne.



Gilmen Smyth earned a BA (Mathematics) from the Université de Moncton in New Brunswick in 1971 and his M.Sc. in Physical Education from Springfield College in Massachusetts in 1978. After a four-year teaching experience in elementary and junior high schools, he obtained in 1976 an appointment with the Department of Physical Education at the Edmundston Campus of the Université de Moncton where he has been teaching since. He is on partial leave from his department to complete his Ph.D. in Biomechanics at the Université de Montréal.



Pierre-A. Mathieu received the B.Sc.A. degree in Electrical Engineering, and the M.Sc.A. and Ph.D. degrees in Biomedical Engineering from the Ecole Polytechnique de Montréal. He did post-doctoral studies at Dalhousie University, Nova Scotia. Since 1973, he has been a Professor in the Biomedical Engineering Institute of the University of Montréal. His research interests were initially on the analysis of intracellular action potential. Later, he became scientifically and administratively involved in a tele-medicine project using the Anik-B satellite. Since 1984, his research activities have been oriented, within the Research Centre of the Montreal Rehabilitation Institute, on EMG signal analysis.