# Estimation of the Range of Motor Units Firing Rates from EMG Signals using a Fourier-based Power Spectrum Technique

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Abstract: A method for estimating the range of the motor units mean firing rates from electromyographic (EMG) recordings is presented. The method is based on classical Fourier spectral estimation techniques and is applied to the 0-50 Hz band of the EMG signal within which the mean MU firing rates are usually observed in sustained contractions. Extensive simulations were performed to account for the influence of different signal characteristics such as the firing rate range (FRR), the number of MUAP trains, the coefficient of variation of the motor unit inter-spike intervals (IPI)) and the noise levels. The number of simulated MUAP trains whose mean firing rate dwelled within the estimated range and the estimation error for the lower and upper extremes of the actual FRR were evaluated. While some peaks were undetected and some inaccuracies in the detected firing rate range were observed, satisfactory results were obtained, as for the vast majority of cases the estimated range corresponded to the actual FRR of the simulated MUAP trains.

## 1 INTRODUCTION

For voluntary muscle activation, the fundamental physiological unit is the motor unit (MU) composed of a motor neuron and its innervated muscle fibres. To be activated, a MU depends on a signal generated in the brain and conducted along the spinal cord. This signal consists in a series of action potentials, which upon reaching the innervated fibres produce muscular action potentials causing the contraction of these fibres. The electrical potential associated with a motor unit firing and captured by an electrode placed in the proximity of the muscle fibres is called motor unit action potential (MUAP) and the series of MUAPs, a MUAP train.

Muscle force modulation in skeletal muscles is due to two mechanisms: the recruitment (activation) and derecruitment (deactivation) of MUs, and changes in the firing rate (i.e., the frequency of occurrence of action potentials in a MUAP train) of active MUs. Extensive experimental work has been carried out to measure the firing rate of MUs from intramuscular EMG recordings and to relate it to different muscles, type and intensity of contraction, subject's age, pathological conditions, fatigue, etc. (Basmajian, 1985).

The straightforward procedure is the so-called MUAP decomposition (i.e., the manual or automatic isolation of one or several MUAP trains from the EMG signal) followed by the statistical evaluation of the MUAP spikes occurrences (Ren, 2006). However this procedure is limited to the capacity of these techniques to resolve precisely different MUAP trains, and this capacity degrades rapidly as muscle contraction intensity gets higher since, with recruitment, the number of MUAPs present in the signal is increased. Detection of MUAPs is even more problematic in surface EMG recordings because the signal results from a larger collection of MUAP trains. Besides, these signals are smoothed by the low-pass filter action of the tissues involved in the volume conduction of the potentials, making more similar the shape for the individual MUAPs, and more difficult the decomposition (Zhou, 2004).

As an alternative to MUAP decomposition, MUs firing rates can be estimated from the EMG power spectrum where a peak, associated to the predominant MU firing rate, may appeared in the 10 to 40 or 50 Hz range. This has been demonstrated in a number of studies: Van Boxtel and Schomaker

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(1983) for the facial and maxilar elevator muscles, Weytjens and Van Steenberghe (1984) for the biceps brachii, Englehart and Parker (1994) for the abductor pollicis. In other cases however, the peaks of different MUAP trains are smoothed or completely eliminated by cancellation (De Luca, 1979, Weytjens and Van Steenberghe, 1984). For this peak to be clearly observed, either the EMG signal is composed by regular MUAP trains with similar firing rate, or it is dominated by a MUAP of large amplitude (De Luca, 1979). With healthy muscles, the first cause is more likely to be present than the second one (Basmajian and De Luca 1985). In neuropathic conditions however, reinervation processes may create MUs composed of an unusual high number of muscle fibres and the second condition may then be present.

Various mathematical models for the EMG signal have been proposed such as the ones of Lago and Jones (1977) and De Luca, (1979) where a MUAP train is modelled by:

$$u(t) = \sum_{k=1}^{n} h(t - t_k) \quad (1)$$

where $h(t)$ is the temporal MUAP waveform and $t_k$ are the time instants where the actual MUAPs occur. Differences between two successive MU firing instants ($t_k$-$t_{k-1}$) are called interpulse intervals (IPIs) and are modelled as independent random variables and thus constitute a renewal process. Under conditions of stationarity, i.e., non-varying $h(t)$ and non-varying IPI probability density function (PDF), the power spectrum of a signal corresponding to a MUAP train is given by:

$$S(\omega) = \frac{1}{\mu}\left\{1 + 2\,\mathrm{Re}\left[\frac{F(j\omega)}{1 - F(j\omega)}\right]\right\} \cdot \left|H(j\omega)\right|^2 \quad (2)$$

where $\mu$ is the mean IPI, $F(j\omega)$ is the Fourier transform of the IPIs PDF and $H(j\omega)$ is the Fourier transform of $h(t)$. Various distributions such as Gaussian, gamma, Poisson and Weibull distributions have been proposed to accommodate experimental data (Merletti and Parker, 2004). All of them lead to one principal peak in the signal power spectrum with additional smaller ones at subsequent harmonics. All those peaks are blurred as the coefficient of variation of the IPI (CVI) increases, particularly as it approaches values of 0.3 (Weytjens and Van Steenberghe 1984).

The features of the EMG power spectrum in relation to the IPI statistical characterization and the degree of stationarity have been amply studied through analytical derivation and simulation (Lago and Jones, 1977), (De Luca, 1979), (Englehart and Parker, 1994). Other studies have been focussed on the statistical relationship between EMG variables, such as the root mean square amplitude or the mean power frequency, and MU firing rates (Christie et al. 2009), (Fuglesang-Frederiksen and Ronager, 1988). However, the influence on the EMG power spectrum of the number of MUAP trains, the mean firing rates of these trains, the CVI and the signal to noise ratio (SNR) has not undergone similar systematic studies.

The aim of this work is to present a method for estimating the frequency range of the firing rates of the set of MUAP trains that compose an EMG signal based on the Fourier power spectrum. The capacity of the approach for varying number of MUAP trains, actual firing rate range (FRR), ICV and noise level was explored through extensive simulation runs using the afore mentioned EMG generation model.

# 2 MATERIAL

10 s-long simulated EMG signals were obtained as the sum of several MUAP trains, each of which generated as the multiple repetition of a given MUAP waveform. Intervals between MUAP occurrences followed Gaussian distributions whose mean was the inverse of the firing rate. The firing rate and the coefficient of variation for each of these trains were set as input parameters in the different analysis tests. MUAP waveforms were taken 'off-the self' from a set of potentials recorded from the deltoid muscles of different patients in a previous study (Rodríguez et al., 2010). White Gaussian noise was added to the signals so that specific levels of SNR could be tested. The sampling rate of the simulated signal was set to 20 kHz.

Different tests were performed to evaluate the performance of the method. In the tests some of the input parameters were given a fixed value while some were varied in a systematic way or randomly within a certain range. Simulations were run 500 independent times for every tested parameter value.

- The first test concerned the detection performance for different FRR values. 10 MUAP trains composed the simulated signals, whose mean firing rates were independent randomly taken in the range [f1-f2], which we will call nominal frequency range (NFR) hereafter. f1 was set to 10 Hz and f2 was varied from 11 to 20 Hz in 1 Hz steps. An SNR of 20 dB, a random variation in the amplitude of the

MUAP waveforms with maximum excursion of 20 dB and an ICV of 0.15 were used.

- The second test was to measure the influence of the number of MUAP trains. This number was varied from 4 to 20 in steps of 2. The NFR was set to [10-15 Hz]. All the other parameters were the same as in the previous test.
- In the third test, the influence of the MU firing regularity was analysed by varying the ICV from 0.03 to 0.3 in steps of 0.03. Fifteen MUAP trains composed the simulated signals whose NFR was also set to 10-15 Hz.
- In the fourth test, the SNR was varied from 0 to 30 dB in steps of 5 dB. Other parameters values were the same as in the previous tests.

# 3 METHODS

As firing rates are located in the low frequency section of the spectrum and to fasten computation, the EMG signals were decimated by a x100 factor. Power spectrum was computed by the Welch's averaged, modified periodogram method, Hayes (1996), implemented in the Matlab Signal Processing Toolbox (version 6.3), using 1s-long signal segments, windowed by a Hamming window and with a 50% overlap between consecutive segments. In Fig. 1A we show in the 0-50 Hz range a typical EMG power spectrum of an EMG signal composed of 10 MUAP trains. Around 10 Hz, three peaks, corresponding to actual MU firing rates can be observed. They are superposed to a smoothly increasing curve, mainly associated to the power spectrum of the MUAP waveforms used to generate the signal. To flatten the spectrum in the 0-50 Hz band, a 5th order polynomial curve was fitted to the power spectrum curve in a mean square basis. The polynomial curve was then subtracted from the spectrum curve, leaving a ‘rectified spectrum’ where the three peaks appeared more clearly for detection (Fig. 1B). On the ‘rectified spectrum’ in logarithmic scale the highest peak ($P_{max}$) was obtained. An interval around $P_{max}$ was determined, in which the ‘rectified spectrum’ was higher than a given threshold. Three different values for this threshold were tested in the experiments: $P_{max}/2$, $P_{max}/4$ and 0 and were and referred as Th1, Th2 and Th3, respectively (Fig. 1B). The 0-50 Hz band was then scan to detect other peaks having a power level higher than $P_{max}/2$.

Frequency intervals around these peaks were then determined following the procedure applied to the highest peak.

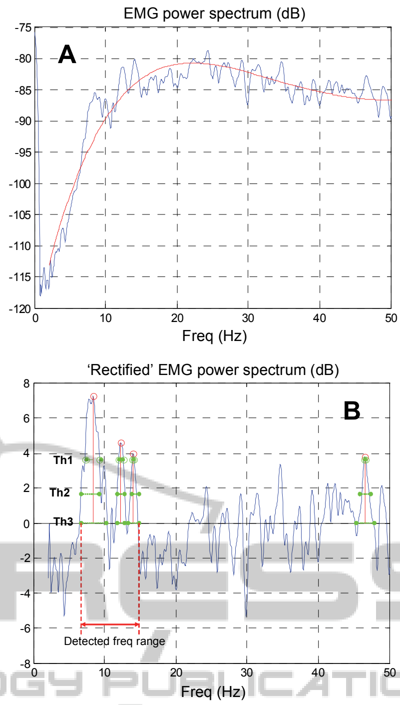


Figure 1: A: EMG power spectrum (logarithmic amplitude) and interpolation curve. B: EMG Rectified spectrum (logarithmic amplitude).

If the highest frequency of any of these intervals was higher than two times the frequency of $P_{max}$, the former interval was discarded, as it could be related to the harmonics of peak frequencies around $P_{max}$. The estimated frequency range was finally obtained by joining together all the remaining intervals and the frequency gaps between these intervals. These gaps could have been produced by valleys of nearby peaks and might contain firing rate frequencies of actual MUAP trains of the EMG signal cancelled by these valleys. As merit figures we measured the following features:

- The number of missed peaks: firing rates of actual MUAP trains of the EMG signal outside the frequency range determined by the method.
- The lower frequency range error (LFRE): difference between the lower extreme of the determined frequency interval and the lower extreme of the FRR calculated as $1/[\mu_1 \cdot (1+\varphi)]$, where $1/\mu_1$ is the lowest mean firing rate of the set of MUAP trains composing the EMG signal and $\varphi$ is the ICV, which was given the same value for all the MUAP trains.

The higher frequency range error (HFRE): difference between the upper extreme of the

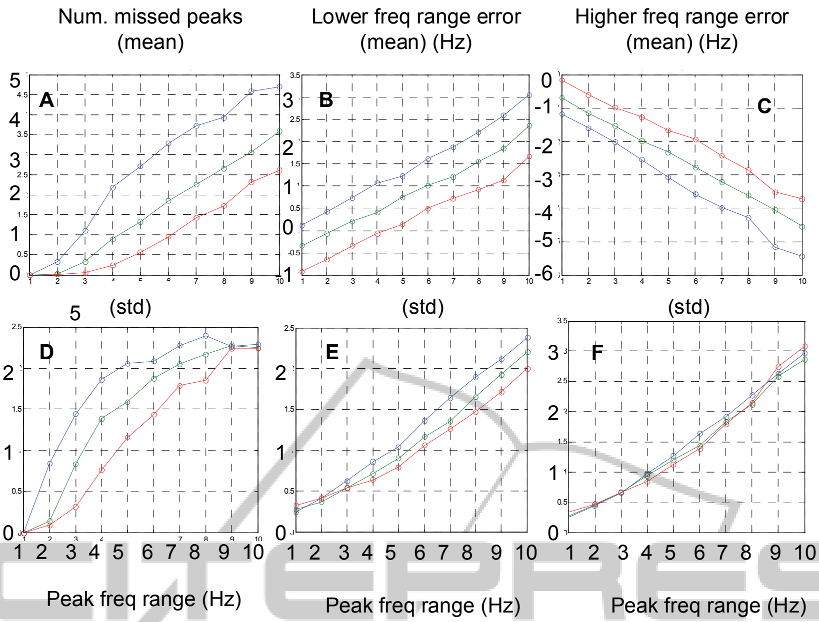


Figure 2: Results of the first test. Blue, green and red curves are respectively for Th1, Th2 and Th3 thresholds.



determined frequency interval and the upper extreme of the FRR, calculated as $1/[\mu_2 \cdot (1-\varphi)]$, where $1/\mu_2$ is the highest mean firing rate of the set of MUAP trains composing the EMG signal.

All simulations were run in the Matlab program (version 7.0.4) (The Math Works, Inc., USA).

## 4 RESULTS

As the FRR increased, a steady degradation of the number of detected peaks was observed (Fig 2.A). Th3 presents the best scores of the three thresholds, with 0.5 missed peaks out of 10 on average for frequency ranges up to 5 Hz and down to 2.5 misses for 10 Hz range. Th2 presents slightly lower detection scores and Th1 shows clearly worse results. The LFRE mean increased almost linearly as the NFR increased, and was highest for Th1 and lowest for Th3 (Fig 2.B). Globally LFRE almost linearly as the NFR increased, and ranged from 0.1 to 3.3 Hz for Th3, from 0.65 to -4.5 Hz for Th2 and from -1.2 to -5.5 Hz for Th1 (Fig 2.C). The variability of LFRE and HFRE, as measured by the STD increased with increasing NFR (Fig. 2.E, F).

The results of the second tests are presented in Fig.3. The mean and STD of the number of missed frequency peaks increased steadily with the number of MUAP trains (Fig 3.A, D). In the case of Th3, the mean was lower than one peak on average for all the studied cases. The number of missing peaks was higher for Th2 and Th1: from 0.5 to 2.4 peaks for Th2 and from 1 to 5.4 peaks for Th1 on average, as the number of MUAP trains varied from 4 to 20. The LFRE increased only slightly with the number of MUAP trains (no more than 0.5 Hz) in the total inspected range and was lower in mean and STD for Th3 than for Th2 and Th1 (Fig 3.B, E). The HFRE decreased slightly with the number of MUAP trains. It was negative in all the studied cases and its magnitude was lower for Th3 than for Th2 and Th1 both in the mean and STD values (Fig 3.C, F).

Results for the third test are given in Fig.4. A moderate increase in the number of missed peaks was observed for the three considered threshold values as the ICV increased and was below 0.2. (Missed peaks were on average below 1, 2 and 4.5 for Th3, Th2 and Th1, respectively). For larger values of ICV, the mean and STD of the number of missed peaks increased more remarkably (Fig 4.A, D). The LFRE mean increased steadily for the three thresholds under study and ICV values up to 0.2 (Fig 4.B). For larger ICV values, LFRE mean remained more or less constant (around 1.5 Hz for Th1, 0.75 Hz for Th2 and 0.25 for Th3). The HFRE variation with ICV decreased around 0 Hz to -7 Hz, indicating considerable underestimation of the upper extreme of the FFR as ICV increased (Fig 5.C). Also the STD of the HFRE increased with the ICV (Fig 5.F).
Results of the fourth test are presented in Fig. 5. Strangely, the number of detected peaks does not vary significantly with the SNR (Fig. 5.A, D).

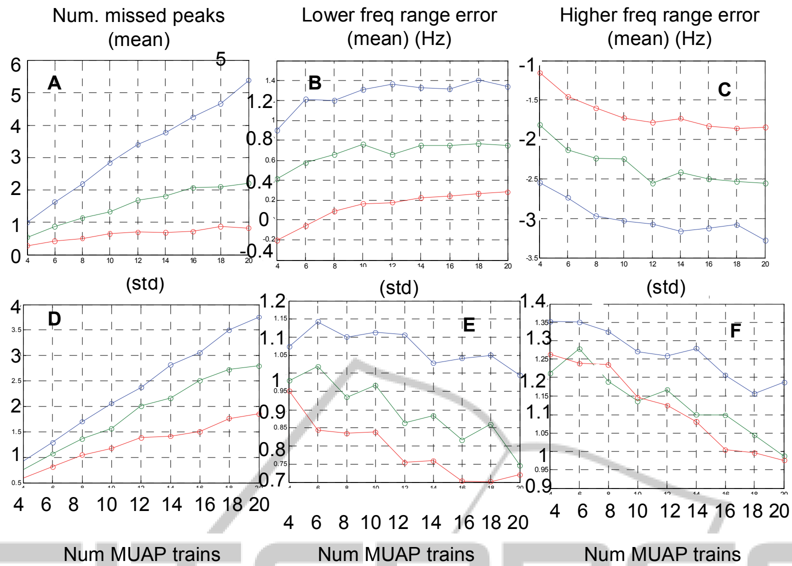


Figure 3: Results of the second test (blue, green and red curves for Th1, Th2 and Th3 thresholds, respectively).



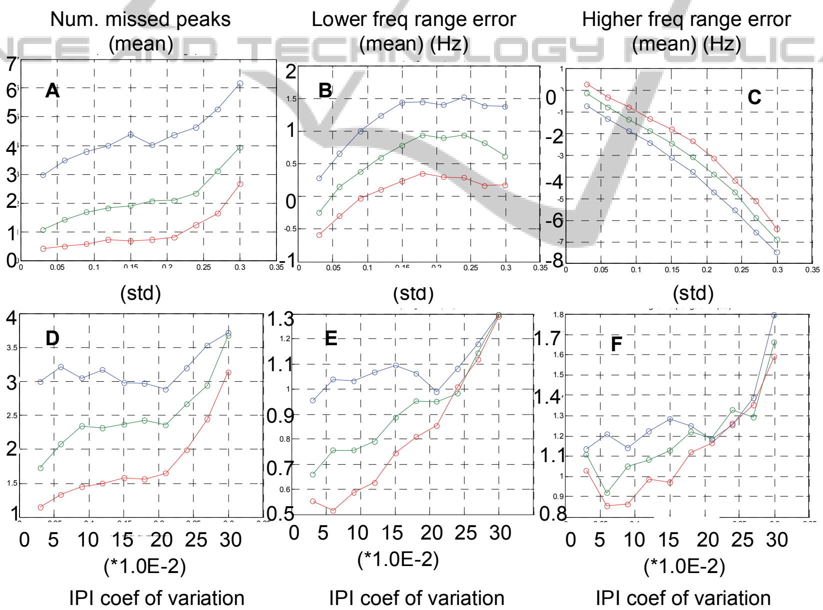


Figure 4: Results of the third test (blue, green and red curves for Th1, Th2 and Th3 thresholds, respectively).

As observed in the previous tests, Th3 had a better performance than the other two thresholds. In fact, Th3 only missed on average 0.5 peaks out of the 15, while Th2 missed around 2 and Th1, around 4. Mean LFRE and HFRE values slightly decreased in mean as the SNR increased and were below 15 dB or more and basically stable for an SNR of 15 dB or more (Fig 5.B-C). LFRE and HFRE STD values were also very stable for the three threshold values (Fig 5.E and 5.F).

# 5 CONCLUSIONS

The main conclusions of this work are:

- A method for estimating the range of the firing rates of the MU trains composing an EMG signal has been produced.
- The method provides satisfactory results as in the majority of studied cases the estimated range corresponded to the actual FRR.

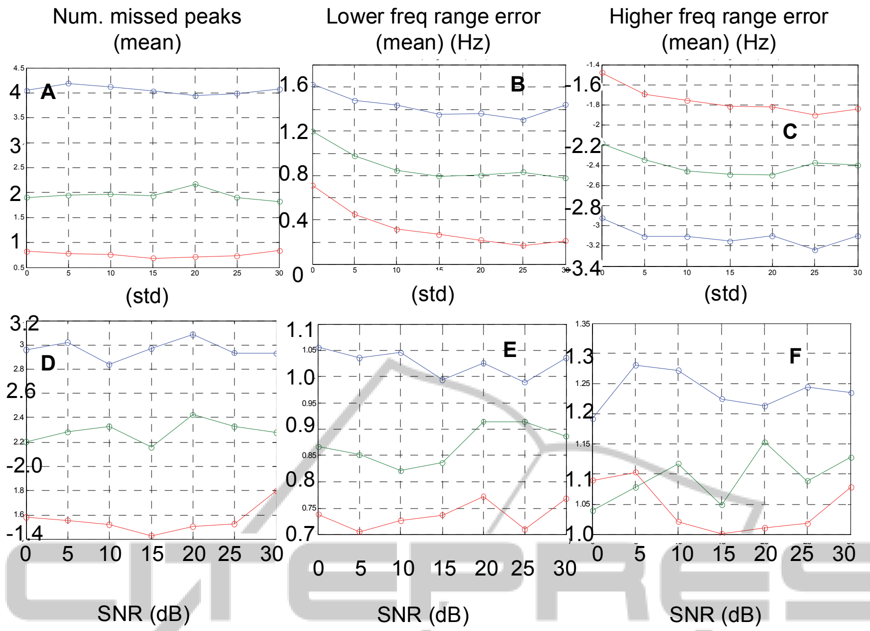


Figure 5: Results of the fourth test (blue, green and red curves for Th1, Th2 and Th3 thresholds, respectively).



- The number of undetected peaks increases as the FRR increases.
- Frequency range absolute errors for LFRE and HFRE tend to increase as the FFR increases.
- The number of undetected peaks increased as the number of MUAP trains increased.
- Frequency range absolute errors for LFRE and HFRE tend to increase slightly as the number of MUAP trains increased.
- As the ICV increased, absolute values for the LFRE and HFRE increased and the number of detected peaks decreased.
- The SNR did not have a significant influence on the detected frequency range nor on the number of detected peaks.

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