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# Sensitivity of the Surrogate Analysis Method to Synchronization and Conduction Velocity of Muscular Fibers

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**Abstract— This paper shows that conduction velocity (CV) and motor unit action potential (MUAP) synchronisation affects the results of Surrogate Analysis (SA). These findings can be used to 1) interpret the result of the surrogate analysis and 2) help evaluate the CV and MUAP synchronisation. A simple dipole-based model for EMG signal simulation is used. It is composed of multiple fibers superposed at the same location, leaving aside any complex geometrical considerations, but putting the emphasis on the timing of the MUAPs firing. Single pulse synchronisation as well as impulse train synchronisation are studied. To highlight the difference between spectral (linear) features, nonlinear features and SA relation with the model parameters, the Median Frequency (MDF), the Kurtosis, the Higuchi's Fractal Dimension (FD) and the FD based SA are compared. The simulation results show that the SA is jointly influenced by CV and the MUAP synchronisation, almost in a multiplicative way. These relations are also more pronounced for an impulse train than for a single pulse. Overall, the SA is shown to be a good feature to consider for CV and synchronisation estimation, uncorrelated with spectral features and moderately with nonlinear features.**

***Index Terms*— Fractal, Features extraction, sEMG sensors, Synchronization, Nonlinear analysis, Conduction velocity, Motor unit action potential, Hypothesis testing.**

## I. Introduction

The Conduction Velocity (CV) and Synchronisation of the Motor Unit Action Potential (MUAP) have been studied for in order to investigate their relations with muscular fatigue [1][2]. The CV and MUAP synchronisation estimation are therefore of interest. These problems have been tackled by spectral (linear) [1] and non-linear features [3-5]. However, it is well known that often linear and nonlinear features can be strongly correlated [6].

The problem of the relation between the power spectrum and nonlinear features is commonly studied by Surrogate Analysis (SA) [7]. The SA is a statistical test which can determine if the value of a nonlinear feature could be obtained from a random time series with similar power spectrum.
The straightforward interpretation [8] of the result is "the nonlinear feature of the time series could not likely have been obtained from a stationary random autoregressive (ARMA) process with the same power spectrum." More loosely, an interpretation linked to the nonlinear feature is often given. Such interpretation have been suggested for EMG signals in [9] where the conclusion that "nonlinear dynamic characteristic can be detected from small data sets of different action surface EMG signals" was drawn.

In this paper, it is suggested that the synchronisation of MUAP is an interesting interpretation of the SA which is linked to the EMG.

A synchronisation interpretation was introduced in [10], showing that the SA could detect non-randomness in the phase spectrum of the Fourier domain. The synchronisation discussed in the present paper uses a time domain synchronisation perspective.

A common approach to evaluate feature performances is the use of simulation where all parameters are known and can be modified independently [11]. Therefore, to highlight the properties of the SA in relation to the CV and synchronization, a very simple, comprehensive model is used. The MUAPs are models as dipoles travelling in an infinite fibre, with the same amplitude and shape and CV. The fibers are modeled to be at the same location, reducing the number of simulation free parameters. Simulations are produced for different CVs, different number of MUAPs, different time windows, for single synchronised impulse timing and impulse train. The effect of the imperfection of synchronisation, modeled as a normal distribution, is also addressed. For each setup, the MDF, the Higuchi's fractal dimension (FD) and the Higuchi's FD based SA are calculated by Monte-Carlo Simulation. It is shown that the Higuchi's FD (FD) based SA is sensitive MUAPs synchronisation. This relation is moreover sensitive to many parameters, particularly the CV where a multiplicative like effect can be observed.

Two main contributions should be outlined: 1) The SA is shown to be suitable for model parameter identification for the first time. 2) Giving a physiological interpretation for the results of the SA is new. Moreover, the scope of the paper could be easily broadened. The findings could have an impact on the study of muscular fatigue and muscular force. Also, it could have eventually applications to EEG and ECG systems.

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Although the method is proposed for the study of muscular activity, the new approach for the synchronization of signals and conduction velocity could be applied in a variety of domain where a blind estimation of synchronization is desired.

The paper is organized as follows: the numerical methods are described in Section II while the simplified EMG model is presented in Section III. The simulations parameters and results are reported in Section IV and discussed in Section V. Finally, Section VI draws some conclusions.

## II. Linear and Nonlinear Methods

This section details the linear and nonlinear features used in this paper. The simpler methods are used for comparison purpose against the more complex nonlinear analysis method. A note on the windowing method used is also given.

### *A) Median Frequency and Kurtosis*

The MDF [4] is obtained from the power spectrum by finding the frequency for which the power below the frequency is equal to half the total power. The MDF is not affected by the data distribution but is sensitive to time domain correlation. The Kurtosis is a basic high order statistic (order 4.) It is not directly affected by time domain correlations but is sensitive to non-normal distribution and especially to extreme values. The MDF and Kurtosis can together represent a large spectrum of the simpler cause that affects nonlinear features.

### *B) Higuchi's Fractal Dimension*

The Higuchi's FD method [12] calculates the slope of the average curve length with respect to the logarithm of the measurement scale. The arbitrary parameters of the method consist of the measurement steps, which can be seen as subsampling ratios. In this paper, these were selected from 1 to 19 at interval of 4. The FD is used here both as a comparison method as well as the drive of the SA presented next.

### *C) Surrogate Analysis*

The SA method [7] compares the FD of the original data to a sampling of the distribution of the FD of surrogate series. The surrogate series were created by the Fast Fourier Transform (FFT) method. The FFT is applied, the phase is uniformly randomized and returned in the time domain by mean of the inverse Fast Fourier Transform (IFFT.) This standard process is shown in Fig. 1 (a). The original series FD is compared to a certain number of surrogate series FD. The null hypothesis that the FD of the original series could be obtained by a linear stochastic process (ARMA) is rejected if it is outside the range of the surrogates FDs. The SA is generally considered to assess that a nonlinear feature measured is caused in fact by an underlying nonlinear process and not simply an ARMA process [5]. However, a lot of information is lost by using a discrete output. It is therefore interesting to study its impact on a continuous valued version of the SA, as proposed in [13]. In this approach, the difference between the original series FD $D$ and the mean of the FD of

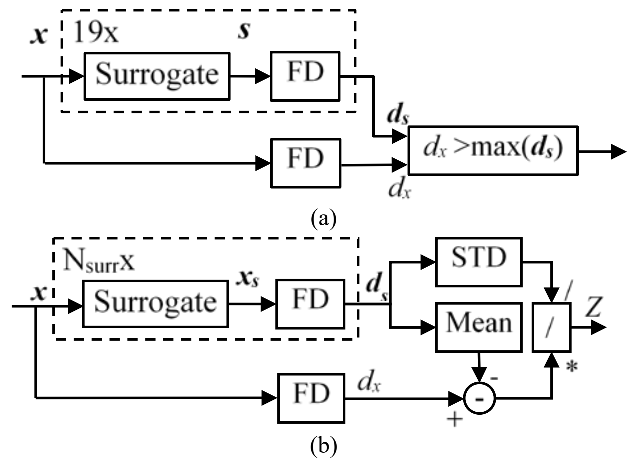


Fig. 1. Schematic of a standard right-sided SA test (a) yielding a discrete (true/false) result. Continuous result version of the SA test (b), giving a score *Z*.

the surrogate series $D_S$ normalised by the standard deviations gives the $Z$ score:

$$Z = \frac{D - \overline{D_S}}{\mathrm{std}(D_S)} \qquad (1)$$

A schematic of this version of the SA is provided in Fig. 1 (b). This score is analogous to the p-value of a t-test. In this paper, the number of 200 surrogate series are generated for the continuous version.

### *D) Windowing*

A windowing method is used to reduce the periodic extension discontinuity artifacts associated with the FFT. The Tuckey window [14] is used with a shape parameter of 0.02. The window was applied to the original and surrogate series. It was also used for the MDF and FD calculations for comparison purpose.

## III. EMG Collinear Biphasic Model

This section presents the model used for generating the signals with emphasis with the synchronization of the action potentials. Geometric considerations are reduced to a minimum in order to focus the attention on the time domain aspects. The model for the single synchronized impulse is described, followed by the modification of the model for synchronized impulse train.

### *A) Single Synchronized Impulse*

The EMG model used is a very simple one. It uses a biphasic action potential model, as described in [14]. The individual fibers are considered as infinite lines. It also assumes that the different fibers are collinear. The biphasic action potential model is composed of a current source and a current sink producing a potential field $\varphi$, as shown in Fig. 2 (from [15]):

$$\varphi(x, y) = \frac{I}{4\pi v}\left(\frac{1}{r_1} - \frac{1}{r_2}\right) \qquad (2)$$

where $x$ is the sensor position in the fiber direction, $y$ is the sensor distance to the fiber, $r_n = \sqrt{x^2 + y^2}$ and $v$ is the medium conductivity. The factor $I/4\pi v$ can be considered constant and ignored in the model. The CV $\sigma$ must however

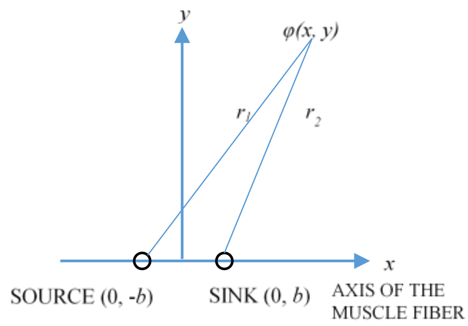


Fig. 2 Dipole model representation. Reproduced from [14].

been taken into account for the propagation of the action potential. A time of arrival $\Delta t$ is included to study the synchronisation. By setting the distance between the sink and source equal to $2b$, ignoring the factor and including the propagation, the potential becomes:

$$\varphi_n(x, y, t) = \frac{1}{\sqrt{\left(x+b-\sigma(t-\Delta t_n)\right)^2+y^2}} - \frac{1}{\sqrt{\left(x-b-\sigma(t-\Delta t_n)\right)^2+y^2}} \quad (3)$$

This basic biphasic action potential is combined either synchronously or non-synchronously. In both case, the signal is composed of a sum of biphasic action potential with varying time of arrival. With $x$ and $y$ kept constant ($x$ can even be set at 0), the multiple fibers action potential is,

$$\psi(t) = \sum_{n=1}^{N_{fibers}} \varphi_n(x, y, t) \quad (4)$$

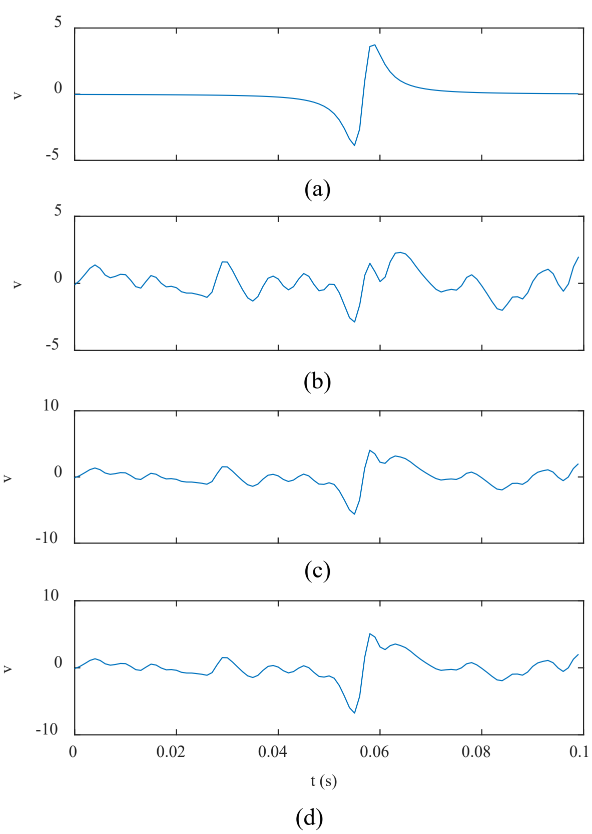


Fig. 3 Example of simulated sEMG signals with a CV of 4 m/s and a **synchronized impulse train of length 1**. In (a), a synchronized signal is shown. In (b), no synchronization is present. The signals in (c) and (d) are linear combination of (a) and (b) for synchronization ratios of 0.5 and 1 respectively.

The difference between the synchronised $\psi_s$ and non-synchronised $\psi_{ns}$ versions of the multiple fibers action potentials lies in the distribution of the time of arrival $\Delta t$. For the synchronised version, a random Gaussian distribution, centered at the center of the time window is used, with a very small standard deviation $\sigma_{sync}$. For perfect synchronisation, this standard deviation is null. For the non-synchronised version, a random uniform distribution is used. To reduce the border effects, the span of the uniform distribution is slightly larger than the time window.

The number of fibers $N_{fibers}$ used for non-synchronised signal affects greatly the validity of the ARMA null-hypothesis, especially when it is low. At the limit, when $N_{fibers} = 1$, the resulting signal is equivalent to a perfectly synchronized signal. The number of fibers is less critical for the synchronised signal.

The synchronization ratio is defined as the power ratio of the synchronized signal to the non-synchronized signals. The fact that a randomly generated non-synchronized signal can, by chance, somehow exhibit synchronisation is ignored, as well as the desynchronizing effect of the standard deviation of the synchronised signal $\sigma_{sync}$. The most realistic way to produce a signal of a certain synchronization ratio would be to vary the number of fibers of the synchronized and non-synchronised parts. However, as the number of action potential can affect the nonlinear characteristics, a

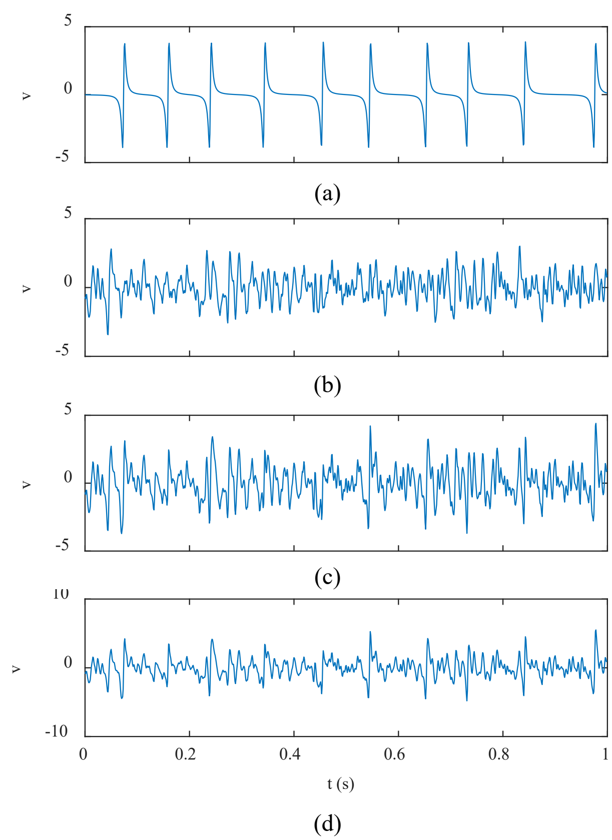


Fig. 4 Example of simulated sEMG signals with a CV of 4 m/s and a **synchronized impulse train of length 10**. In (a), a synchronized signal is shown. In (b), no synchronization is present. The signals in (c) and (d) are linear combination of (a) and (b) for synchronization ratios of 0.5 and 1 respectively.

TABLE I CONSTANT PARAMETER THROUGH ALL SIMULATIONS

| | | |
|---|---|---|
| Sampling Frequency | $f_{samp}$ | 1 kHz |
| Muscle Fibre to Sensor Distance | $y$ | 1 cm |
| Source/Sink Distance | $b$ | 0.025 cm |
| Synchronous Pulses Time Stdev | $\sigma_{sync}$ | 0.01 s |
| Inter Pulse Stdev | $\sigma_{\tau}$ | 1e-4 s |
| N Impulse Signals not Synchronized | $N_{fibers}$ | 100 |
| N Impulse Signals Synchronized | $N_{fibers}$ | 100 |

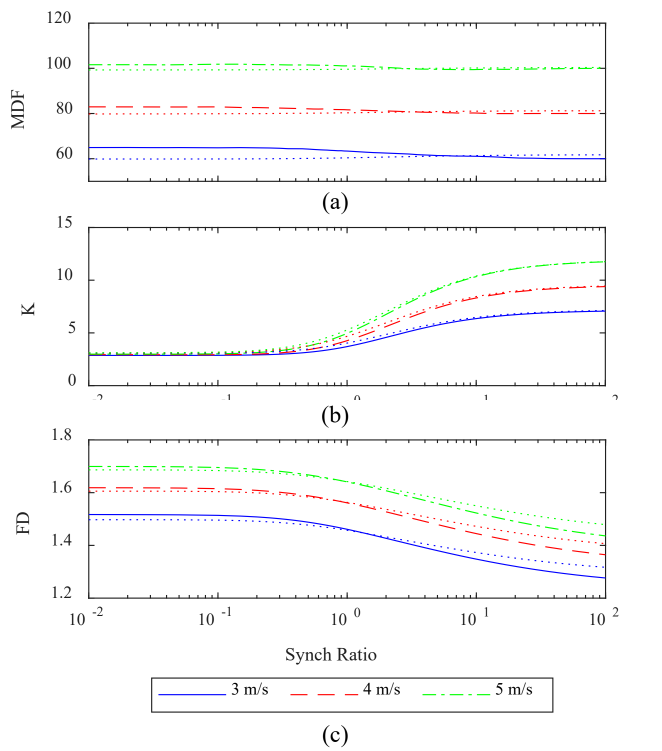


Fig. 5 Basic features vs synchronization ratio for different CV. The line styles given in the legend are for a synchronized impulse train length of 1 while the dotted lines have a length of 10. The MDF (a), Kurtosis (b) and FD (c) are shown. 1000 Monte Carlo iterations are used for each point.

synchronisation ratio scaling parameter ($\gamma$) approach is rather chosen:

$$\psi_{\gamma} = \sqrt{\gamma}\psi_{s} + \psi_{ns} \quad (5)$$

The signals $\psi_s$ and $\psi_{ns}$ are normalized before the scaling. The sum $\psi_{\gamma}$ does not need to be normalized, since the different features used in this paper are invariant to scaling.

### *B) Synchronized Impulse Train Model*

The model used for the impulse train is similar to the one described previously. The impulse train $\psi_t$ is generated by replicating $L_{train}$ times the synchronized signal $\psi_s$ at a regular interval $\tau$. A variability of this interval is added, modeled as a variable $\Delta\tau$ with normal distribution of standard deviation $\sigma_{\tau}$:

$$\psi_t = \sum_{l=1}^{L_{train}} \psi_s(t - \tau - \Delta\tau_l) \quad (6)$$

The time windows become larger as the train becomes longer. In this paper, the number of fibers for the non-synchronised signal is scaled by the length of the impulse train when its length varies. Because the fibers are considered collinear, this is equivalent to a fiber that fires multiple times (with overlapping action potential allowed.) As previously the scaling approach is used for combining the normalized synchronised and non-synchronised signals:

$$\psi_{\gamma} = \sqrt{\gamma}\psi_{t} + \psi_{ns} \quad (7)$$

Examples of the different signals involved are given in Fig. 3 for a length 1 synchronized impulse train and in Fig. 4 for a length 10 synchronized impulse train for a CV of 4 m/s. The other parameters are given in the next section.

## IV. SIMULATIONS

This section shows the numerical experiments realized to highlight the properties of the SA with regard to the synchronization ratio, synchronized impulse train length and CV in comparison to the other features.

### *A) General parameters*

Although the model used is quite simple, some parameters were set constant throughout all simulations to simplify the comparison. An overview of the simulation parameter is given in Table I.

### *B) Simulation results* of basic features

The MDF, Kurtosis and FD's synchronization ratio impact are shown in Fig. 5. The mean value over 1000 Monte Carlo simulations is presented. The signals used are have a train length of 1 and 10.

Although the MDF varies with the SR, it is most likely due to windowing effect. There is much more windowing effect for unsynchronized. Also, the longer the train, the lower the windowing problem. This can explain why long train results are almost flat. However, if the MDF is not sensitive to synchronization, it is strongly dependant on conduction velocity.

The Kurtosis varies with synchronization. This variability is stronger as the CV is increased. When no synchronisation is present, the CV does not affect the Kurtosis. Hence, the CV can be seen as a multiplicative factor of the effect of the synchronization. The mean of the Kurtosis is not affected by the train length.

The FD is modified by the CV and synchronization independently. The mean of the FD is only slightly affected by the train length.

The effect of the standard deviation of the train length on the basic features are discussed in the sensitivity analysis section.

### *C) Simulation results for the Surrogate Analysis*

The effect of the synchronization ratio and the CV on the SA are shown for the discrete version of the SA in Fig. 6 and the continuous version in Fig. 7.

The results for train lengths of 1 and 10 are shown. It is clear that as in the Kurtosis case, a multiplicative effect between the CV and the SA relation to synchronization ratio is present. However, this relation is even stronger when the train length increases. Residual windowing problems still can be seen for the single impulse version, especially at low CV.

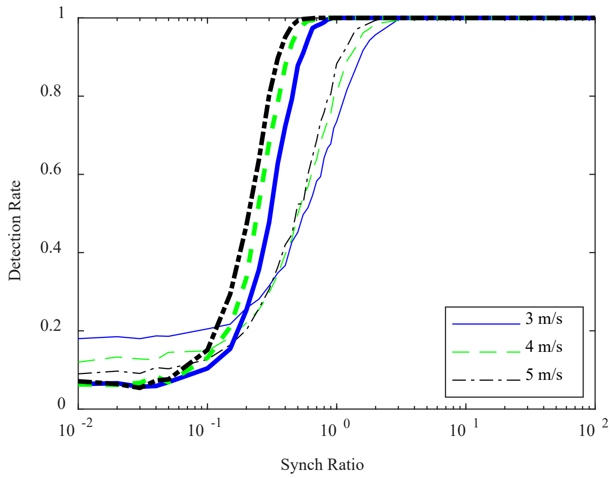


Fig. 6 Detection rate of the discrete version of the SA vs the synchronization ratio at different CV. The thin lines are for synchronized impulse train length of 1 and thick lines for impulse train length of 10.

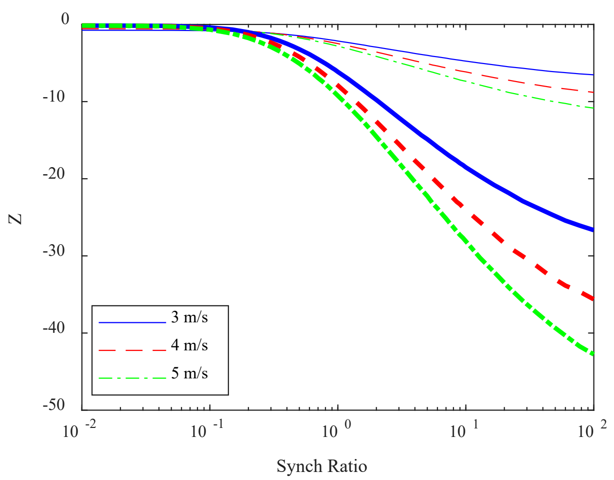


Fig. 7 $Z$ score of the continuous version of the SA vs synchronization ratio for different CV. The thin lines are for synchronized impulse train length of 1 and thick lines for impulse train length of 10.

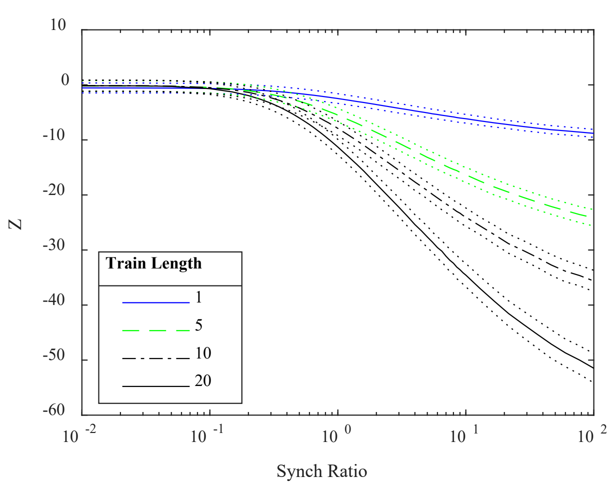


Fig. 8 $Z$ score of the continuous version of the SA vs synchronization ratio at a CV of 4 m/s for different synchronized impulse train length. The dotted lines shows the ±1 standard deviation limits.

The train length effect is targeted in the results presented in Fig. 8. Again, as for the CV, some kind of multiplicative effect is seen, this time between the train length and the synchronization effect on the mean SA result.

### *D) Sensitivity Analysis*

The sensitivity operator $S$ with respect to the synchronization of a feature $f$ is defined as the derivative of the mean of the feature with respect to the synchronization divided by the standard deviation of the feature:

$$S\{f\}(\gamma) = \frac{1}{\text{std}(f)} \frac{df}{d\gamma}. \quad (8)$$

In this paper the derivative calculated by using the forward difference between two simulated points. The sensitivity was not sampled at regular steps but were the same for every feature tested.

The Fig. 9 shows the sensitivity of the SA for different synchronized train length. It is clear that for longer impulse train the sensitivity becomes greater. Also, the sensitivity is at its peak when the synchronization ratio is around 0.3.

The Fig. 10 shows the sensitivity of the four features for a train of length 10. In a large range, the SA has the highest sensitivity. The sensitivity of the MDF is most likely due to border effects. For a synchronization ration of 0.1, the SA sensitivity of the SA (7.8) is twice larger than the sensitivity of the Kurtosis (3.5), the second most sensitive feature.

### *E) Correlation between the features' residuals*

A correlation matrix of the different features residuals was studied in order to explore the possibility of using multiple features to increase the sensitivity. The less correlation, the more likely it is possible to combine the different features. A single example is given in Table II for a CV of 4 m/s, a synchronization ratio $\gamma$ of 1 and a train length $L$ of 1. The correlation matrix was built with 30000 Monte Carlo iterations. A bootstrap method was used to assess the precision of the correlation matrix elements. With 10000 bootstrap resampling iterations, the maximum standard deviation of the element of the correlation matrix was 0.0061. The results obtained, with a maximum correlation of 0.44 between the FD and SA shows that there is a possible gain to use multiple features together. It is noteworthy that such correlation matrix is different when varying the simulation parameters.

## V. Discussion

The first use of the findings of this paper is to add a possible interpretation of the SA applied to signals that can involve a synchronization similar to the EMG case. The CV effect does not change the interpretation of the SA but make it more sensitive to the synchronization. However, from the SA alone, it is not possible to distinguish between synchronization and other already existing explanation of the SA positive results such as real underlying nonlinear behaviour or time-varying phenomenon [16]. This aspect presented in this paper would be still valid on more realistic models.

A second use of the SA/synchronization/CV relationship is in the estimation of the synchronization and CV. However,

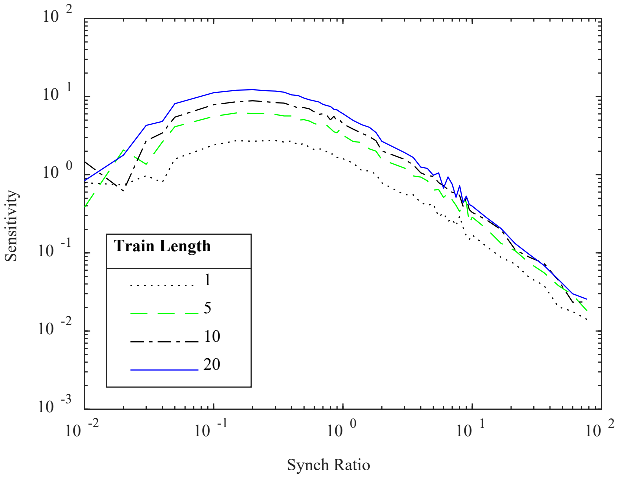

Fig. 9 Sensitivity of the SA with respect to the synchronization ratio for different synchronized train length.

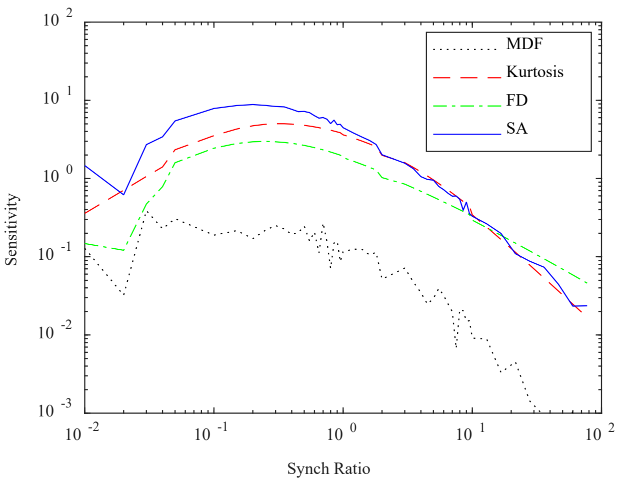

Fig. 10 Sensitivity of the SA with respect to the synchronization ratio for different features at a synchronized train length of 10.

TABLE II CORRELATION BETWEEN FEATURES RESIDUALS FOR TRAIN LENGTH OF 1, CV = 4 AND SR = 1, FOR 10000 MONTE CARLO ITERATIONS.

| Features | MDF | Kurtosis | FD | Z SA |
|---|---|---|---|---|
| MDF | 1.0000 | -0.0265 | 0.6674 | 0.0557 |
| Kurtosis | -0.0265 | 1.0000 | -0.0230 | -0.1372 |
| FD | 0.6674 | -0.0230 | 1.0000 | 0.4405 |
| Z SA | 0.0557 | -0.1372 | 0.4405 | 1.0000 |

since this inverse problem has not been tackled here, it has not been shown in this paper if the use of SA allows better estimation. It has been showed that the SA residuals are not strongly correlated to the other features' residuals. It is not clear however if the SA contains more information that a group of simpler features. If the SA contains effectively different information than simpler method, the inverse problem would be the most interesting application of this paper.

But, the first question that would arises is the performance of the SA in relation to the EMG model. There is probably an effect between the distance and synchronization similar to the relation between the CV. The real question however is the impact of having different fibers at different distance, and possibly with different CV. For this situation, even the notion of synchronization should be redefined. Test should hence been made on gradually more realistic models [11][17].

A sensitivity analysis to common interference signal such as Power Line Interference (PLI) and electrocardiogram (ECG) should also be performed. An optimisation of the windowing method and size should also be made. The effect of white noise, which can have a large impact on nonlinear features [18] should be investigated with regards to the sensitivity of the SA to synchronization and CV.

If the information about the synchronization ratio can help for classification purpose, the use of SA is appropriate for feature extraction. Without recovering the exact synchronization ratio and CV, the feature can be used in a similar manner as was presented in [13].

The approach allows to study the conduction velocity and the synchronization of the MUAPs when the muscular activity is strong. The large literature on the study of these aspect is restricted to the cases where the MUAPs can be resolved individually, therefore only for weak muscular activity.

Lastly, no optimization of the non-linear feature has been made to maximize the sensitivity of the FD and the SA to the CV and synchronization. Also, other nonlinear features could be considered. A group of nonlinear features, with different parameters and their SA could be used to identify the parameters of complex models.

Form this discussion, it can be seen that although the model used here was far from realistic, the parameters used in the SA were far from optimal. It is expected that as the SA is optimized and joint with multiple features, it could have the power of identifying the parameters of more complex models.

## VI. CONCLUSION

This paper showed a new interpretation of the surrogate analysis: the synchronisation of the MUAPs. The model used was chosen in order to lead to an obvious interpretation of the results. In more complex scenarios, the interpretation of the SA will not be so clear. However, when the SA is used to analyse any action potential type signals, the synchronisation should generally be considered. This paper showed also that the SA is an interesting candidate for the estimation of motor unit characteristics such as the synchronisation and CV. Probably, other higher-level characteristics like muscular fatigue, which is linked to synchronisation and CV could be approached in the same way by the SA. The remaining question is to find the part of the information contained in the SA which is not already present in linear and classical nonlinear features, or rather can the SA can be combined to the MDF and FD to obtain better resolution in the joint estimation of the synchronisation and CV.

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