Proceedings of the 28th IEEE
EMBS Annual International Conference
New York City, USA, Aug 30-Sept 3, 2006

Effects of Force and Joint Angle on Fractal Parameters of the Myoelectric Signal

Mehran Talebinejad[1,2], Adrian D. C. Chan[2], *Senior Member IEEE*,
Ali Miri[1], *Senior Member IEEE*, and Richard M. Dansereau[2], *Member, IEEE*
[1]*School of Information Technology and Engineering, University of Ottawa, CANADA*
[2]*Department of Systems and Computer Engineering, Carleton University, CANADA*

Abstract—**In this paper we investigate the effect of force and joint angle on myoelectric signal parameters. In recent years, methods that have been previously used to analyze nonlinear chaotic dynamical systems have been applied to myoelectric signals. Nonlinear myoelectric signal parameters that have been used include the fractal dimension, estimated using the Katz method and Box-Counting methods, and the spectral slopes. Previous research has only examined effects of contractile force, whereas this research also includes joint angle effects. Results of this research suggest that the Katz and Box-Counting approaches used to estimate fractal dimension are not well suited for time functions, such as myoelectric signals. Results from the spectral slope parameters suggest that these parameters can track joint angle effects. A generalized model approach building upon the spectral slope method is proposed for future work.**

I. INTRODUCTION

MYOELECTRIC signals (MES) are electrical signals associated with the contraction of a muscle. They can be monitored non-invasively using electrodes on the surface of the skin, providing useful information regarding the muscles. For example, it is well established that as the contractile force of a muscle increases the root mean square (RMS) of the MES increases [1]. Spectral analysis of MES also reveals that the spectrum tends to shift towards the lower frequencies during muscle fatigue [1]. Muscle fatigue can therefore be monitored by spectral parameters such as the median frequency.

Analyses of MES are complicated by many confounding factors during dynamic contractions. For example, the median frequency is influenced muscle fatigue but is also dependent upon force and joint angle [2]. The influence of the various factors, however, may not manifest significantly in all MES parameters; therefore, if suitable MES parameters can be obtained, it is possible to take into account effects from confounding factors.

Methods used for fractal analysis have been researched for their application for physiological data [3]. More recently, fractal analysis methods have been applied for analyzing myoelectric signal (MES) [4]-[7]. In these previous works, an estimated fractal dimension (eFD) was used to parameterize the MES. Fractal dimension provides a method of quantifying signal complexity. In [4] and [5], the eFD was computed using the Katz method [8]. Their results demonstrated that the MES eFD is highly correlated with force.

In [6], the eFD was computed using the Box-Counting method [9]. Again, a correlation was found between the eFD and force. The Box-Counting method for computing the eFD was also applied to simulated MES, revealing a correlation between eFD and the number of active motor units, and a correlation between eFD and the firing rate of active motor units [7]. Force production is regulated by two main factors: 1) spatial recruitment (number of active motor units); and 2) temporal recruitment (firing rate of active motor units); therefore, this result again correlates eFD with force.

The correlation found between eFD, computed using the Katz or Box-Counting methods, and force is not surprising. The Katz method computes the eFD as,

$$eFD = \frac{\log(N)}{\log(N) + \log(d/L)} \tag{1}$$

where N is the number of points in the digitized MES sequence, d is the farthest distance between the first point and any other point on the MES waveform, and L is the sum of the distances between successive points [8]. The Katz method is not well suited for computing the eFD for a time functions because the eFD is highly dependent upon the waveform length, and constant amplitude scaling will have a significant effect on the estimate.

The Box-Counting method for computing the eFD is also not appropriate for time functions, as the dimensions it works upon are not easily related (i.e., time and signal amplitude). Constant amplitude scaling will also result in an increase in the eFD. In addition, the eFD computed using the Box-Counting method saturates for fractal dimension 0.5 above the topological dimension [9], [10]. This saturation in eFD is noticeable in the results of both [6] and [7], and is increasingly severe for shorter waveform sequences.

In [11], the $1/k^{\beta}$ behavior of the MES power spectrum was examined by computing the slope of the spectrum on either side of the spectral peak. Two parameters were defined: 1) α_{left} is the slope of the approximated line for the lower frequencies; and 2) α_{right} is the slope of the approximated line for the higher frequencies. These parameters were referred to as fractal indicators. While these parameters were found to be sensitive to force effects they appeared to be insensitive to fatigue effects.

In this paper, we examine the effect of both force and joint angle on MES parameters. The MES parameters are the eFD, computed using the Katz and Box-Counting methods, and the α_{left} and α_{right} parameters.

II. METHODS

A. Data Collection

Data were collected from five healthy males (age 22 to 29; average age 25). MES were recorded from the belly of the *biceps brachii* of the right arm using surface Duotrode electrodes (Myotronics, USA, model 6140), an Ag-AgCl electrode pair spaced 1.9 cm apart. An Ag-AgCl Red Dot electrode (3M, USA, model 2237) was placed on the elbow as a reference electrode. MES were amplified (Grass-Telefactor, USA, model 15A54) and sampled at 1000 Hz using a 12-bit analog-to-digital converter board (National Instruments, USA, model PCI-6071E). The amplifier's variable gain was adjusted between 10 and 100, such that the maximum dynamic range of the analog-to-digital converter was utilized without over ranging. The amplifier's filters were set with a bandwidth of 1 Hz to 300 Hz.

A central pulley apparatus (Fig. 1) was used to elicit constant force contractions at four joint angles (60°, 90°, 120° and 150°, where 180° is considered full elbow extension). Two weights were used in this study: 5 lb (2.27 kG) and 7.5 lb (3.41 kG), requiring a force of 31 N and 47 N on the handle, respectively, to maintain a constant joint angle. Each contraction was held for 15 seconds and there was at least 1 minute of rest between each trial to avoid muscle fatigue. Each subject repeated the contractions for all eight joint angle-force combinations three times. Joint angle-force combinations were randomized to avoid ordering effects.

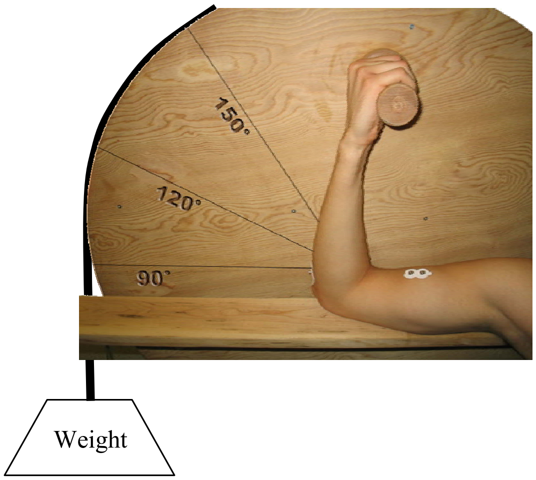

Fig. 1. Central pulley apparatus, used to apply constant force at specific joint angles.

B. MES Parameters

The eFD was computed for the Katz method, using (1). The eFD computed for the Box-Counting method was performed by first covering the MES by square boxes with side lengths of $1/2^m$, where m is the recursion number (an integer between 1 and 8 for this study). The slope of the least squares line of the bi-logarithmic plot of the number of boxes versus the box side length (i.e., bi-logarithmic derivative) was then computed; this slope is the Box-Counting eFD.

To compute the α_{left} and α_{right} parameters, the peak frequency (i.e., frequency of the power spectrum's maximum) was determined from a power spectrum estimate from the modified Welch method, using a 500 ms Hamming window and 50% overlap between windows. The spectral slopes were computed using a least squares line fit on the power spectrum estimate from the Yule-Walker method, with a 6th order autoregressive model. Results of the least squares line was found to be more consistent, with lower variance, using the Yule-Walker power spectrum estimate, compared to the Welch method, whereas the estimated peak frequency was found to be more accurate using the Welch power spectrum estimate.

III. RESULTS

The MES parameters (i.e., RMS, eFD computed using the Katz and Box-Counting methods, α_{left}, and α_{right}) are plotted as a function of joint angle in Fig. 2. The RMS value has a minimum at a joint angle of 90º. This is expected as there is an optimal length for muscle fibers at which they can generate maximum force. This can be explained in terms of the sliding filament mechanism and their overlap which affects a number of cross bridges in the overlap region and hence the produced force [8]). At other joint angles, force production is not optimal and requires an increase in the number of active motor units or firing rate, resulting in the increase in RMS. As expected, the RMS value is higher for the higher weight.

Results of the eFD computed using the Katz method reveals a relationship with the joint angle that strongly resembles the RMS value. This is indicative of the Katz method being highly dependent on the signal amplitude.

The results of the eFD computed using the Box-Counting method suggests that there exists no consistent relationship with joint angle. While the eFD averaged across subjects may appear to have a positive correlation with joint angle, this relationship is not consistent between subjects. This lack of any trend is likely due to the saturation of the eFD, which limits its range.

Similar to the eFD computed using the Box-Counting method, the α_{left} parameter does not show a consistent relationship with joint angle. For this parameter, α_{left} averaged across subjects appears to have a negative correlation with joint angle. This trend is seen for individual subjects; albeit, with a fair amount of variance.

Results for the α_{right} parameter suggest that there is a negative correlation with joint angle. Comparing the α_{right} with the RMS plot, the α_{right} parameter does not seem to have a simple linear relationship with the RMS value. The α_{right} parameter does have a consistent relationship with force. Increasing force increases the magnitude of the slope, which is not unexpected. With increased force, one would anticipate an increase in the overall power of the spectrum but with a fairly fixed bandwidth associated with MES the result would be an increase in magnitude of the spectral slope.

Statistical analysis of the MES parameters was performed using an ANOVA. The results are summarized in Table I. Both force and joint angle have significant effects for the RMS and eFD computed using the Katz method. Significant effects for both parameters are also shown for α_{right}; however, only a significant joint angle effect appears for α_{left}.

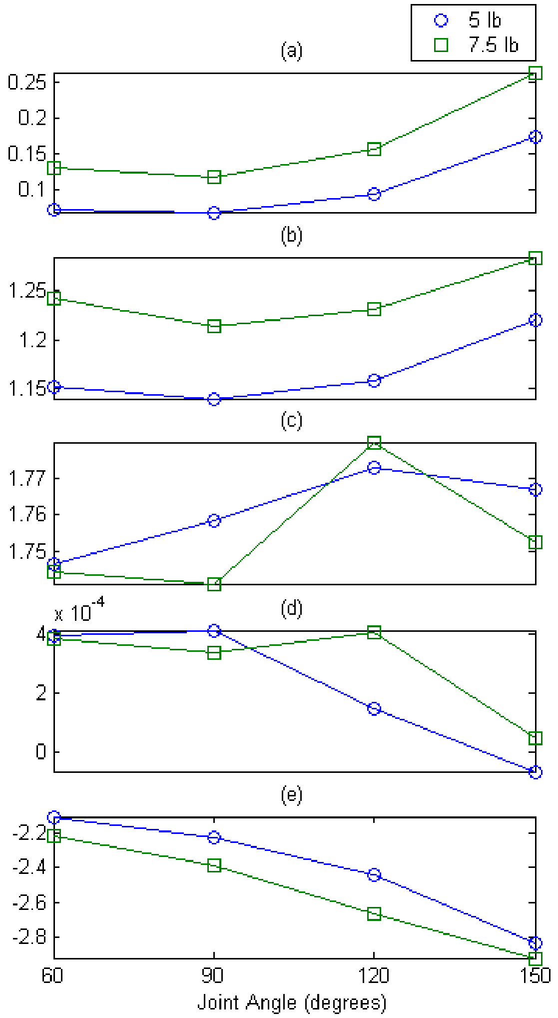

Fig. 2. Myoelectric signal parameters averaged over the five subjects as a function of joint angle (a) root mean square; (b) eFD computed using the Katz method; (c) eFD computed using the Box-Counting method; (d) α_{left}; and (e) α_{right}.

TABLE I

ANOVA ANALYSIS OF MYOELECTRIC SIGNAL PARAMETERS (P-VALUES WITH SIGNFICANT EFFECTS SHOWN IN BOLD; $\alpha_T = 0.05$)

Myoelectric Signal Parameter	Force	Joint Angle
RMS	**0.005**	**< 0.001**
eFD (Katz)	**0.007**	**< 0.001**
eFD (Box-Counting)	0.450	0.164
α_{left}	0.260	**0.040**
α_{right}	**0.011**	**0.001**

IV. DISCUSSION

This research investigated fractal parameters of MES as a function of force and joint angle. Based upon work previously reported in literature, these parameters included the eFD, which was computed using the Katz and Box-Counting methods; however, it appears that these methods are not well suited for estimating the fractal dimension for time functions. The fundamental problem is the disparate axes on which the eFD is computed upon (i.e., time and amplitude). Results suggest that the eFD computed using the Katz method simply produces a measure that is closely related to the RMS value. As a result, the utility of this parameter is diminished. The eFD computed using the Box-Counting method suffers from an inherent problem of saturation when applied in these circumstances. The eFD may not saturate for lower force levels; however, it is expected, from previously reported results that this eFD would also be closely related to the RMS value. This is due of the amplitude dependency of the Box-Counting method when applied to time functions.

The behavior of the spectral parameters α_{left} and α_{right} appears to be encouraging. Results suggest that the α_{left} parameter may be able to discern force and joint angle effects; however, these results are fairly variable. The α_{right} parameter shows a significant effect from both force and joint angle, but the behavior differs from the RMS value. This suggests that the α_{right} parameter is capturing geometric effects in addition to force effects. These results for α_{left} and α_{right} are consistent with simulation results reported in [13]. In [13], the α_{left} and α_{right} parameters were found to be significantly affected by motor unit depth but not by the number of active motor units and firing rate.

The α_{left} and α_{right} parameters are referred to as fractal indicators in [11] because these parameters are the slope of the power spectrum in a bi-logarithmic plot, and are therefore related to the $1/k^{\beta}$ behavior of the signal. In [8] and [9], a general power spectral density function is proposed for signals whose spectrum does not conform to a simple $1/k^{\beta}$ law. This general model is:

$$P(k) = \frac{c|k|^{2g}}{\left(k_0^2 + k^2\right)^q} . \qquad (2)$$

Clearly, when $g = 0$, $k_0 = 0$, and $1 < q < 2$, this model reduces to a simple $1/k^{\beta}$ model. For nonzero values of g and k_0, the properties of self-similarity and self-affinity are applicable in a restrictive manner for this general model, where the eFD of the signal can be related to the parameters g and q [8], [9]. The parameter g can be thought of as the parameter dictating the low frequency behavior. The parameter q can be thought of as the parameter dictating the high frequency behavior; however, the model equation does couple the parameter g with the high frequency behavior. This general model provides a clearer relationship between the MES parameter and fractal geometry compared to the spectral slopes.

Estimation of the parameters g, q, and c can be performed using a standard least squares approach that minimizes the logarithmic least squares estimate [8], [9]. Difficulties in linearizing $P(k)$ to k_0 requires that k_0 be determined in an iterative manner with the parameters g, q, and c. It appears, however, that the least squares approach cannot be directly applied to MES. Variability in the power spectral estimate and data limited to the "knee" of the model causes the method to diverge.

In our future work we propose a modification to the general model, as shown in (3). This modification has the advantage of decoupling the effect parameter g has on the high frequency behavior of the model. It is expected that a standard least squares approach for estimating the model parameters for MES would not converge for the same reasons that plague the original model.

$$P(k) = \frac{c\left|k/k_0\right|^{2g}}{\left((k/k_0)^2 + 1\right)^{q+g}} . \tag{3}$$

V. CONCLUSIONS

The eFD parameters computed using the Katz and Box-Counting method have been previously used to analyze MES; however, their application to MES does not seem to be appropriate. These methods for computing the eFD are not suited for time functions. A high dependency on the signal amplitude causes these methods to produce a parameter that closely resembles the RMS value. With the Box-Counting method there is also the problem of saturation.

The spectral slope parameters, α_{left} and α_{right}, demonstrate potential to provide a method of discerning different factors that can influence the MES (e.g., force, joint angle, muscle fatigue).

Additional work is required to robustly evaluate the spectral slope parameters using a larger data set. A general power spectral density model has also been proposed as an alternative method to the spectral slope method. Parameters of the model can be related to the spectral slope and therefore, are expected to have the same value as a MES parameter. In addition, using a model based approach, results are expected to have more consistency and perhaps provide more insight into the process of MES generation.

ACKNOWLEDGMENT

The work was supported by the Natural Sciences and Engineering Research Council (NSERC) of Canada.

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