

Detection of an increase in EMG regularity during fatiguing contractions

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Abstract: The changes in the evolvement patterns of surface electromyography (EMG) signals during both static and dynamic fatiguing contractions are studied. The main finding is that the EMG signal tends to be more and more regular as muscle fatigues. An increase in the summation of all the regular evolvement patterns denoted by D_{reg} reflects such a tendency. Compared with traditional measurements, D_{reg} shows less variability among subjects when characterizing a fatigue process. In addition, the calculation of D_{reg} in the time domain is free from the restrictions disturbing those of spectral parameters. The detection of an increase in the EMG regularity not only proposes a new and easy way to inspect changes in EMG during the fatigue process, but also provides strong supports to estimate muscle fatigue by means of nonlinear analysis methods such as entropy and complexity measures. The detection method of signal regularity can also be applied to other physiological signals.

Key words: muscle fatigue; surface electromyography (EMG); regularity

The examination of changes in the surface electromyography (EMG) signal has been extensively accepted as a window to the assessment of localized muscle fatigue. One of the most commonly studied changes in EMG is an increase in the EMG amplitude represented by the average rectified value (ARV) or the root mean square (RMS) of the signal. However, contradictory changes in the EMG amplitude characteristics of fatigue were reported in Ref. [1]. Another well-known characteristic for fatigue assessment is the power spectrum of EMG. A variety of studies shows a shift towards lower frequencies of the EMG power spectrum (also represented as a spectrum compression) during fatiguing contractions. A decrease in mean power frequency (MNF) or median power frequency (MDF) is often used to indicate such a spectrum shift. Nevertheless, while numbers of researchers accept spectral parameters as indicators of muscle fatigue, some others have questioned the use of power spectral measures for fatigue assessment, particularly at low contraction levels or during dynamic contractions^[2-3]. Anyway, a very important point when using the MNF or MDF measures is that the estimation of spectral variables is affected by a number of factors, such as the method

used and the size of the analysis window introduced by the power spectral density (PSD) estimation^[4]. Moreover, since stationarity of the signal is a prerequisite for performing common spectral analyses, fairly short durations of EMG signals are used to satisfy the quasi-stationarity assumption. When frequency parameters are determined over a finite length of the signal, a random error and sometimes a systematic error or bias is introduced^[5].

Changes in the EMG magnitude have been suggested to be able to better represent underlying motor unit activity during fatigue than changes in the power spectrum do^[6]. In this paper, we investigate the evolvement patterns of the EMG time course during both static and dynamic muscle contractions. To the best of our knowledge, no such study has been undertaken in the literature. The purpose of this paper is to offer a new way to inspect changes in fatiguing EMG and to propose a new direction in finding easy and reliable indices of localized muscle fatigue by means of the surface EMG signal.

1 Materials and Methods

Two groups of healthy male students volunteered in this study. None of the subjects had any history of neuromuscular disorder and each gave his informed consent before participating. The subjects were seated on the bench with the handgrip and seat level adjusted to maintain an elbow flexion angle of 90°. The eighteen students in the first group performed one isometric contraction at 60% MVC (maximum voluntary contraction) as long as possible, and the eight students in the second one were asked to pull the handgrip repetitively at 45% MVC. Ag/AgCl electrodes were used to record EMG signals. Each bipolar electrode pair had a diameter of 5 mm with a constant interelectrode distance of 2 cm. The electrode pair was located over the biceps brachii of the dominant arm, and the reference electrode was placed on the top side of the wrist. The skin of the interested site was cleaned by alcohol with a gentle abrasion beforehand. Differential amplifiers with bandpass filters between 10 and 500 Hz were used to reduce noise. And the sampling frequency was 1 kHz.

1.1 Evolvement pattern analysis^[7]

Given a time series $\{u(t), t = 1, 2, \dots, T\}$ of EMG recordings, we can obtain a series of observation sequence $\{u_j(k), k = 1, 2, \dots, l\} (j = 1, 2, \dots, T - l + 1)$ by sliding a window with length l . For each observation step j , we sort the observation sequence in an increasing order $\{u_j(k_1), u_j(k_2), \dots, u_j(k_l)\}$. When any equality $u_j(k) = u_j(k + i)$ occurs, the observations are ordered according to the sequence of their occurrence. With the ordinal arrangement signed down, each observation sequence is then matched to

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a symbolic sequence $\pi = [k_1, k_2, \dots, k_l]$.

For each evolutionment pattern π of the EMG time course, we can calculate the relative probability or proportion of pattern π among all the evolutionment patterns as

$$P(\pi) = (T - l + 1)^{-1} \#(\pi)$$

where $\#(\pi)$ represents the total occurrence times of pattern π , and $T - l + 1$ denotes the total occurrences of all the evolutionment patterns. Summing up the relative probabilities of the regular evolutionment patterns and those of the irregular evolutionment patterns, we define

$$D_{\text{reg}} = P([1, 2, \dots, l]) + P([l, l-1, \dots, 1])$$

$$D_{\text{irreg}} = \sum P(\pi) \quad \pi \neq [1, 2, \dots, l] \text{ and } \pi \neq [l, l-1, \dots, 1]$$

Generally, the higher proportion of regularity changes a signal has, the more regular it appears. So D_{reg} reflects the regularity degree of the EMG signal, and D_{irreg} implies the irregularity degree of the EMG signal contrarily. Since the total probability of all the evolutionment patterns equals 1, D_{irreg} can also be simply obtained from the subtraction of D_{reg} from 1.

$$D_{\text{irreg}} = 1 - D_{\text{reg}}$$

1.2 Processing of EMG data

In order to monitor the changes of $D_{\text{reg}}/D_{\text{irreg}}$ versus time, surface EMG signals are first segmented into non-overlapping consecutive epochs. Then $D_{\text{reg}}/D_{\text{irreg}}$ is calculated for each epoch under a given observation window, and its slope and intercept are provided by least-square error linear regression. Different epoch lengths ranging from 100 to 3 000 ms are analyzed repeatedly for the EMG signals during static contractions, whereas the epoch lengths for the EMG during dynamic contractions are determined by the time duration of one single pulling action.

To make a comparison with traditional fatigue indices, changes in ARV, RMS, MNF, and MDF variables are also examined. The calculation of these variables can be referred to Ref. [4]. For the MNF and MDF estimation, Welch's modified periodogram method is used to estimate the PSD.

In recent years, much research has been done on the increase of % DET (a descriptor measuring the amount of determinism in recurrence quantification analysis) during a fatigue process. Here we also investigate the changes of % DET during fatiguing contractions. The parameters selection of % DET computation is as follows: the delay parameter is selected at 4; the embedding dimension is set to 10; the radius is 10% of the rescaling maximum distance; and the line parameter is set to two points. For the EMG signals of static contractions, the epoch length is invariably selected at 1 000 points and the shift parameter is set to 500 points. For the EMG signals of dynamic contractions, the epoch length and shift parameter are equivalent to the time duration of one single pulling action.

The reproducibility and reliability of the six EMG fatigue variables (ARV, RMS, MNF, MDF, % DET, and D_{reg}) among different subjects are checked through normalized slope S_N and normalized intercept I_N , which can be calculated as

$$S_N = \frac{S}{S_0}$$

$$I_N = \frac{I}{I_0}$$

where S is slope, and I is intercept; S_0 , I_0 are the first values of corresponding EMG variables obtained at the beginning of the contraction.

2 Results

Fig. 1 illustrates the changes in D_{reg} during one static sustained contraction. Each point in the figure denotes a single

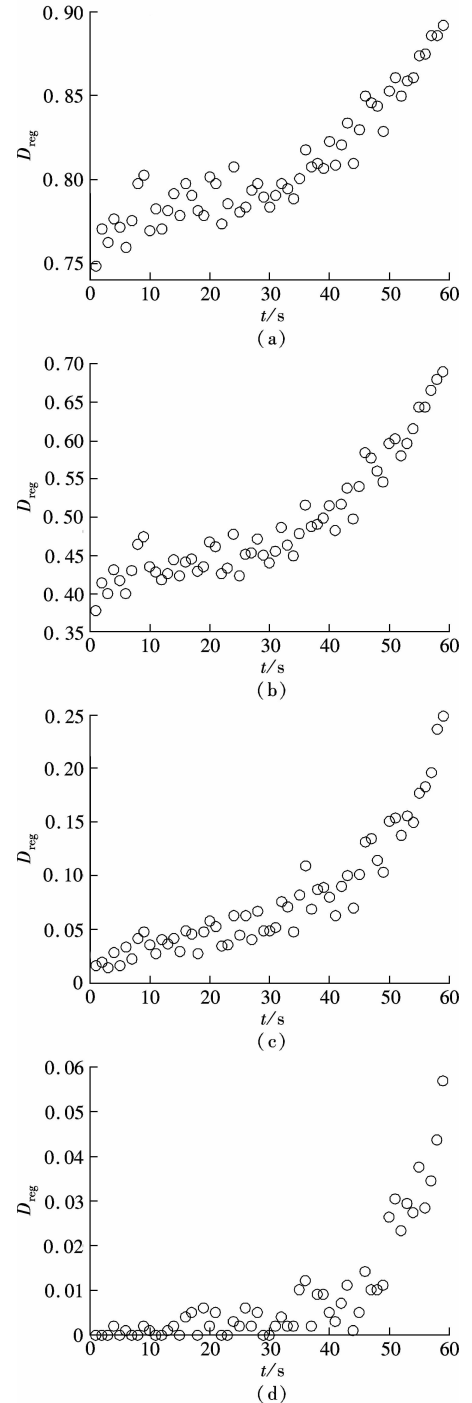


Fig. 1 Changes in D_{reg} vs. time during one static sustained contraction at 60% MVC. (a) $l=3$; (b) $l=5$; (c) $l=10$; (d) $l=15$

D_{reg} value of the corresponding epoch, with its epoch length being 1 000 ms. An increase in D_{reg} of the EMG signal can be found for each contraction test. For example, under the observation window length $l=3$ in Fig. 1(a), the regression line of D_{reg} ascends from 0.754 6 to 0.861 8. In Fig. 2 similar changes in D_{reg} of EMG signals can be found during a dynamic repetitive pulling action, where the regression line of D_{reg} increases from 0.793 8 to 0.876 6. Here the epoch length is 550 ms and the observation window length is $l=3$.

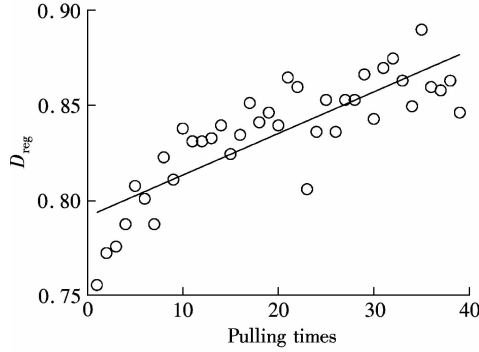


Fig. 2 Changes in D_{reg} vs. time during one dynamic repetitive pulling action at 45% MVC

Fig. 3 depicts the values of variables S_N and I_N during the static contractions for all the 18 subjects. Since the pair of ARV and RMS, and the pair of MNF and MDF give similar results, only RMS and MDF are shown in the comparison for clarity. The figure shows that RMS may rise with time ($S_N > 0$) in one subject's test, whereas it may also fall with time ($S_N < 0$) in another subject's test. So when measuring the fatigue process, RMS shows a lack of reproducibility and reliability, which is consistent with previous works^[8-9].

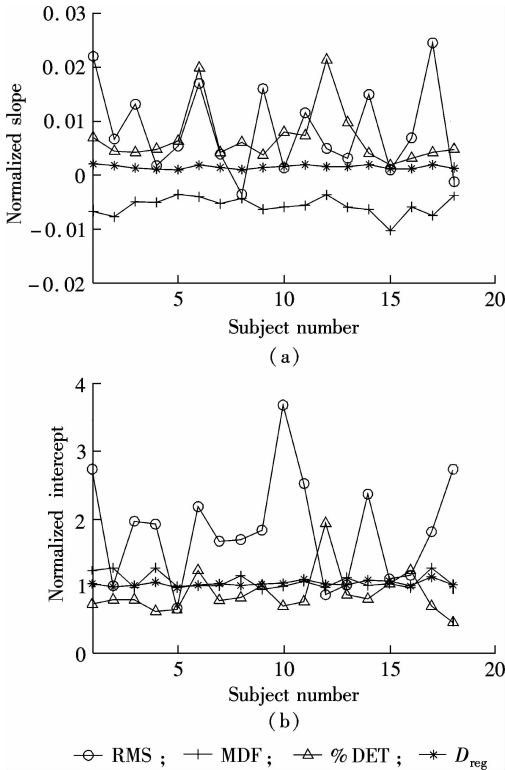


Fig. 3 Values of the normalized slopes and normalized intercepts of EMG variables during the static sustained contractions

The other EMG variables show similar changes among different subjects; that is, MDF decreases with time ($S_N < 0$), and D_{reg} as well as % DET increases with time ($S_N > 0$). However, they differentiate with each other in their variations among subjects. % DET shows the largest oscillation among different subjects; MDF comes next, and D_{reg} exhibits the smallest variation.

Fig. 4 shows the boxplots for the distribution of the values of S_N/I_N in Fig. 3. The upper and lower ends of the center box indicate the 75th and 25th percentiles of the data, and the line in the box indicates the median. The ends of the vertical lines indicate the minimum and maximum data values unless outliers are present. The point “+” means a maximum of 1.5 times the inter-quartile range. The distributions of the values of S_N/I_N in the figure further imply that the variability of RMS between subjects is much bigger than those of MDF, % DET, and D_{reg} . Among the latter three, D_{reg} possesses the smallest variability, and the variabilities of MDF and % DET are close.

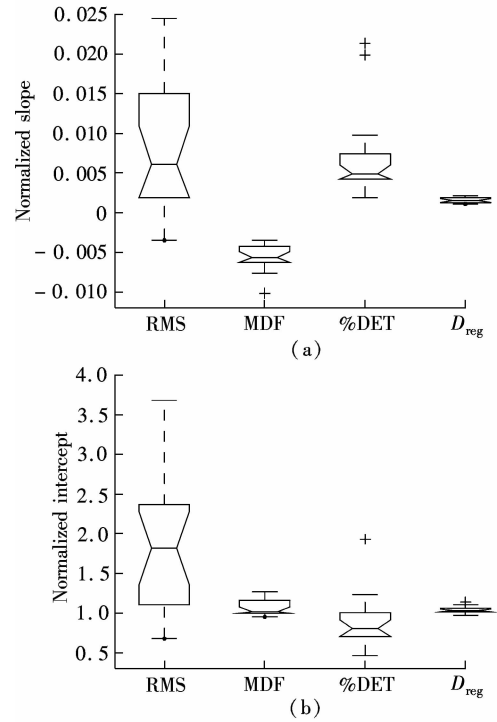


Fig. 4 Boxplots for the normalized slopes and normalized intercepts in Fig. 3

Performances of the EMG variables in assessing fatigue during dynamic repetitive contractions (see Fig. 5) are similar to those during static sustained contractions. RMS still exhibits the largest variability among different subjects. Unlike that during static contractions, MDF performs worse than % DET when characterizing fatigue during dynamic contractions. Two factors may be responsible for the poorer performance of MDF during dynamic contractions. One is the problem of the nonstationarity of EMG. The other is that, the movement of the body segments causes a relative displacement of the electrodes with respect to the underlying muscle fibers, which affects the frequency content of the EMG signal. Among the four variables, D_{reg} still shows the smallest variation.

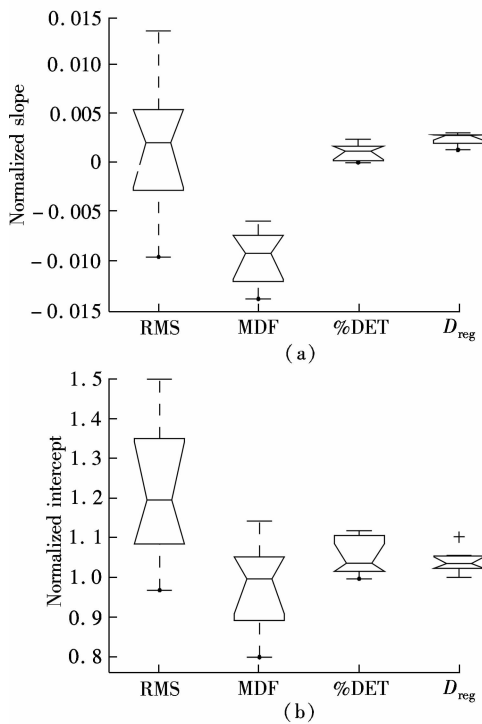


Fig. 5 Boxplots for the normalized slopes and normalized intercepts of EMG variables during repetitive pulling contractions

3 Discussion

Two parameters should be selected for the calculation of D_{reg} . One is the epoch length, and the other is the length of observation window l . The difference in epoch length has not much influence on the D_{reg} analysis. The values of D_{reg} obtained under different observation windows show different increasing natures. Besides that, under the observation window $l = 3$, Fig. 1 also shows how D_{reg} changes with time under other different observation windows of $l = 5, 10, 15$, using the same epoch length of 1 000 ms. From Fig. 1 we can see that all the D_{reg} values grow with time no matter whether the observation window is short or long. However, D_{reg} becomes smaller with greater l values, since it is less likely to find steady changes under these windows. In the meantime, the longer the window is, the more slowly the D_{reg} grows. In Fig. 1 (d) where $l = 15$, D_{reg} remains at a nearly constant value near to zero at the beginning, and then climbs slowly with the passage of time. Not until the contraction is sustained for 40 s does D_{reg} show an evident increase. Under still longer observation windows such as $l = 20$, D_{reg} is even lower, and its increase is only visible in the latter stages of the contraction. In the future, maybe we can utilize the increasing nature of D_{reg} under different observation windows to assess the stages of muscle fatigue. For instance, during the early stages of fatigue, values of D_{reg} under short observation windows evidently increase while those under long windows almost maintain constant values. As fatigue progresses to the middle stage, the values of D_{reg} under long observation windows begin to increase. Only when the muscle is in the late stage of fatigue, will the values of D_{reg} under both short and long observation windows show obvious increases.

The parameter D_{reg} seems to provide a new good perspective on EMG changes during the fatigue process. The small variations in both S_N and I_N of D_{reg} imply that, when characterizing the fatigue process between subjects, D_{reg} owns better reproducibility as well as reliability than the traditional fatigue indices and the nonlinear index % DET. In addition, as the parameter D_{reg} is calculated in the time domain, the calculation has no restrictions like those of spectral variables. Based on the aforementioned, we conceive the parameter D_{reg} as a new valuable EMG characteristic of muscle fatigue. It is expected to assess localized muscle fatigue together with other variables such as MNF or MDF, or even serve as an independent fatigue indicator.

The increase in the EMG regularity during the fatigue process is in agreement with other proposed techniques such as the decrease of the first Lyapunov exponent (L1)^[10], the increase of fractal characteristics and the % DET of the recurrence quantification analysis (RQA)^[11–12], because an increase in signal regularity indicates a decrease in the complexity of the signal. As the conclusion is drawn from limited tests, more studies are still needed to test its validity under more muscle contraction conditions.

4 Conclusion

This paper presents a first study of changes in the evolution patterns of surface EMG signals during both static and dynamic fatiguing contractions. The finding of this study is that the EMG signal tends to be more and more regular as muscle fatigue progresses. In all the static and dynamic fatiguing tests in this study, D_{reg} , the summation of evolution patterns in order and in reverse order, ascends as the muscle fatigues.

The detection of increased regularity in fatiguing EMG may provide strong support to estimate muscle fatigue by examining changes in EMG signal complexity. A much wider area may then be opened to investigate muscle fatigue from the point of view of nonlinear analysis. For example, nonlinear measures based on entropy, which reflects system complexity, can be explored to assess muscle fatigue. Combination measurements of the time domain analysis with entropy (such as symbolic entropy), or combination of the time-frequency analysis with entropy (such as wavelet packet entropy) can then be used to better characterize a muscle fatigue process from both linear and nonlinear aspects.

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疲劳收缩过程中 EMG 信号规则度增加的检测

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摘要:研究了肌肉静态及动态收缩过程中表面 EMG 信号演化模式的变化,发现了疲劳进程中肌电信号趋于规则性变化的规律,信号的所有规则性演化模式之和(以 D_{reg} 表示)的增加反映了该规律. 与传统的疲劳指标相比, D_{reg} 在刻画不同人体的肌肉疲劳时变异性更小. 此外,基于时域的 D_{reg} 的计算可以避免传统频域指标的使用局限性. EMG 信号规则度增加的发现,不仅为检测疲劳进程中 EMG 信号的变化提供了一种新的简易方法,更为以往工作中通过非线性指标(包括熵和复杂度等)来评估肌肉疲劳提供了有力的证据. 介绍的信号规则度检测方法同样适用于其他生理电信号.

关键词:肌肉疲劳;表面肌电;规则度

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