Original Article

The Comparison between Spectral and Entropic Measures Following Fatigue in Erector Spinae Muscles

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ABSTRACT

Background: Surface electromyography (sEMG) of muscles is a non-invasive tool that can be helpful in the assessment of muscle function and some motor control evaluations. A loss of force, known as muscle fatigue is accompanied by changes in muscle electrical activity. One of the most commonly used surface EMG parameters which reflects paraspinal muscle fatigue during different tasks and positions is median frequency. Although it is widely known that the electromyography power spectrum shifts to lower frequencies during fatiguing contraction, an opinion exists that the validity of spectral shifts in assessment of fatigue is questionable. Some researchers have examined whether other quantities derived from sEMG signals are better indicators for muscle fatigue. Following cyclic flexion/extension and consequence fatigue, variation in sEMG signals may be complex for study.

The aim of this study was to determine which of the median frequency (MF) or entropic (ENTR) is more sensitive for measuring muscular fatigue in erector spinae muscles during cyclic flexion/extension.

Methods: Surface electromyography of erector spine muscles was recorded in 25 healthy subjects during cyclic dynamic contractions. The experimental session consisted of two parts: measurement of Maximal Voluntary Contraction (MVC), and performing the fatigue test. All subjects performed rhythmic flexion/extension with 50% MVC loading against B-200 Isostation, about 4-6 minutes. The MF and ENTR of the muscle activities were computed to assess muscular fatigue.

Results: Paired sample t-tests showed that MF and ENTR changes after fatigue test were significant (P<0.001). Percentage changes of both MF and ENTR were reduced, this reduction for ENTR was more than 40% (P<0.001).

Conclusion: It seems that the changes of ENTR in muscle activities have the ability to measure muscular fatigue and is more sensitive in comparison to MF.

Introduction

Surface electromyography (sEMG) of muscles is a non-invasive tool that can be helpful in the assessment of muscle function and some motor control evaluations [1-4]. A loss of force, known as muscular fatigue is accompanied by changes in muscle electrical activity [5]. The signals recorded during a sEMG test from surface electrodes are the instantaneous algebraic summations of action potentials from muscle fibers. These signals

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are recorded and then processed with a power spectrum analysis algorithm [6]. One of the most commonly used surface EMG parameters which reflect paraspinal muscle fatigue during different tasks and positions is median frequency. The Median Frequency is calculated from the spectrum and reflects the propagation speed of the action signal [7]. Fatigue causes a decrease of the frequency content of the sEMG signal usually described as a decline of the mean or median frequency of the power spectrum [8,9]. Although it is widely known that the electromyography power spectrum shifts to lower frequencies during fatiguing contraction, an opinion exists that the validity of spectral shifts in assessment of fatigue is questionable [10]. Some researchers have examined whether other quantities derived from sEMG signals are better indicators for muscular fatigue. In general, there are a number of existing methods based on time domain, frequency domain and techniques for standard EMG analysis [11-16]. Nonlinear analysis of surface EMG signal has been exploited by some researches and indicates a good measurement for EMG analysis [7,17,18]. Shannon information analysis, described by Eckmann et al. [19] is a technique for detection of state changes in drifting dynamic systems [20]. Shannon entropy is a standard measure of complexity and has been applied in cognitive science research, aging studies, heart failure research, and other fields [21-23].

Methods

Twenty five asymptomatic male subjects participated in our cross-sectional study. They were all healthy without any previous history of LBP or other musculoskeletal and neuromuscular diseases. The study was approved by the Human Research Ethics Review Committee, Tehran University of Medical Sciences, Iran. Informed consent was obtained from each subject prior to participation. The anthropometric data of the subjects are presented in Table 1.

Table 1: Anthropometric measures of the subjects (n=25)

Variables	Mean±SD	Range
Age (year)	25.2±2.8	20, 30
Height (cm)	170±5	165, 182
Weight (kg)	69.6±3.7	64, 76
BMI (kg/m²)	23.3±1.6	19.9, 26.9

In this study, Electromyography, Isoinertial Dynamometer and Lumbar Goniometry were synchronized with each other.

Electromyography: The activities of Lumbar muscles were monitored using an eight-channel portable sEMG data logger (Type NO. P3X8, DataLog, Biometrics Ltd, Cwmfelinfach, Gwent, UK). The EMG signals were recorded with four pre-amplified, bipolar active electrodes (Type NOS.SX230, Biometrics Ltd, Cwmfelinfach, Gwent, UK) with a fixed center-to-center inter electrode distance of 20 mm, built-in differential amplifier with a gain of 1000, input impedance of 10^{15} ohms, common

mode rejection ratio of 110 dB at 60 Hz and bandwidth of 25–450 Hz, without notch filter and sampling frequency of 1kHz. Disposable reference electrodes were placed on the left wrist. Signals were digitally recorded by the data loggers on 256 MB flash memory.

Lumbar goniometry: Lumbar range of motion was monitored using an eight-channel portable movement analyzer data logger (Type NO. P3X8, DataLog, Biometrics Ltd, Cwmfelinfach, Gwent, UK). The lumbar motion was recorded with one twin axial strain gauge goniometer (Type SG150/B, Biometrics Ltd, Cwmfelinfach, Gwent, UK), accuracy ±2º, and repeatability 1º and sampling frequency of 1 kHz.

Isostation Dynamometer: The B200 Isostation, (Isotechnologies Inc., Hillsborough, N.C), is a triaxial dynamometer for measuring torque, range of motion and velocity in three planes. Subjects were positioned in standing posture in the B200 Isostation, with the lumbosacral junction aligned with flexion/extension axis of the machine. Subjects were firmly restrained from movement by using the straps and pads provided, according to the instructions recommended by the manufacturer.

Each subject was assessed in two sessions at least one day apart: a familiarization and an experimental session. The familiarization session included several Maximal Voluntary Contractions (MVC) by isometric trials in extension/flexion and five free load dynamic flexion/ extension movements (without placement of surface electrodes). The experimental session consisted of two parts: 1) measurement of MVC, and 2) performing the fatigue test.

1) *Measurement of MVC:* After shaving and abrading skin with alcohol on the electrode sites, the surface electrodes were positioned bilaterally over the belly of the two pairs of lumbar trunk muscles, including right and left mulifidus (MU-R, MU-L) and longissimus (LO-R, LO-L). The electrodes were positioned according to recommendations of SENIAM of the European Union (Surface Electromyography for the Non-Invasive Assessment of Muscles is a European concerted action in the Biomedical Health and Research Program), and parallel with the muscle fiber orientation. The electrodes for MU were placed at the level of L5 spinous process (about 2-3 cm far from the midline) and for LO were placed at 2 finger width lateral from the spinous process of L1. Then the subjects were stabilized in the B200 Isostation dynamometer. EMG data were saved for off-line analysis.

Subjects were required to do maximum isometric contraction against B-200 Isostation in about 30 degree of forward flexion for MVC of lumbar extensor muscles. Three MVC performed each in 10 second with 20 second rest between them. Maximum torques of this three MVC was selected for calculation of 50% MVC and resistance of fatigue test. Surface electromyography (sEMG) was recorded simultaneously.

2) *Fatigue test:* All subjects performed rhythmic flexion extension with 50% MVC loading against B-200 Isostation, about 4-6 minutes. If the subject was not able to

continue the test because of fatigue, the test was stopped. Verbal encouragement was given throughout the test for all subjects. During fatigue test surface electromyography was recorded.

Data Analysis

The sEMG data were full-wave rectified and smoothed with the time constant of 51 ms to yield linear envelops by data Logger software. Threshold level of 5% of maximum amplitude of concentric muscular activities was used to determine the onset and the end of their activities.

Fast Fourier transform (FFT) was done for frequency analysis. For detection of muscle fatigue; MF of lumbar extensor muscles in cyclic dynamic activities were obtained before and after fatigue test.

One dimension, two line, one delay were used to detect Shannon information (entropy) for nonlinear measurements of dynamic activities of lumbar extensor muscles. Duration of muscles activities, before and after fatigue were different, therefore the durations divided into 100 equal-sized, and then the probabilities (P_i) from the average rectified values of sEMG of each muscles during concentric activities were determined.

Because the mean square displacement is related to the entropy S of the signal, $S \sim \ln \Delta$ (where ln denotes the natural logarithm), the plateau value can be used to characterize the sEMG signal. The entropy was calculated as Shannon Entropy equation $S = -\sum P_i \ln P_i$ (Figure 1).

SPSS 17 was used for statistical analyses of data. Parametric data analyses t-test were used, since the data were normally distributed as Kolmogorov-Smirnov test (KS) indicated. Pearson's correlation analysis (r_s) was selected to analyze the degree of association between variables. The alpha level was set at 0.05.

Results

Descriptive and inferential statistics of the MF and entropy (ENTR) of muscle activities before and after fatigue test are shown in Table 2. Kolmogorov-Smirnov test (KS) indicated normal distribution. Paired sample t-tests showed that changing of MF and ENTR following being fatigued were significant (P<0.001). Percentage changes of both MF and ENTR were reduced, this reduction for ENTR was more than 40% (P<0.001) (Table 3).

Discussion

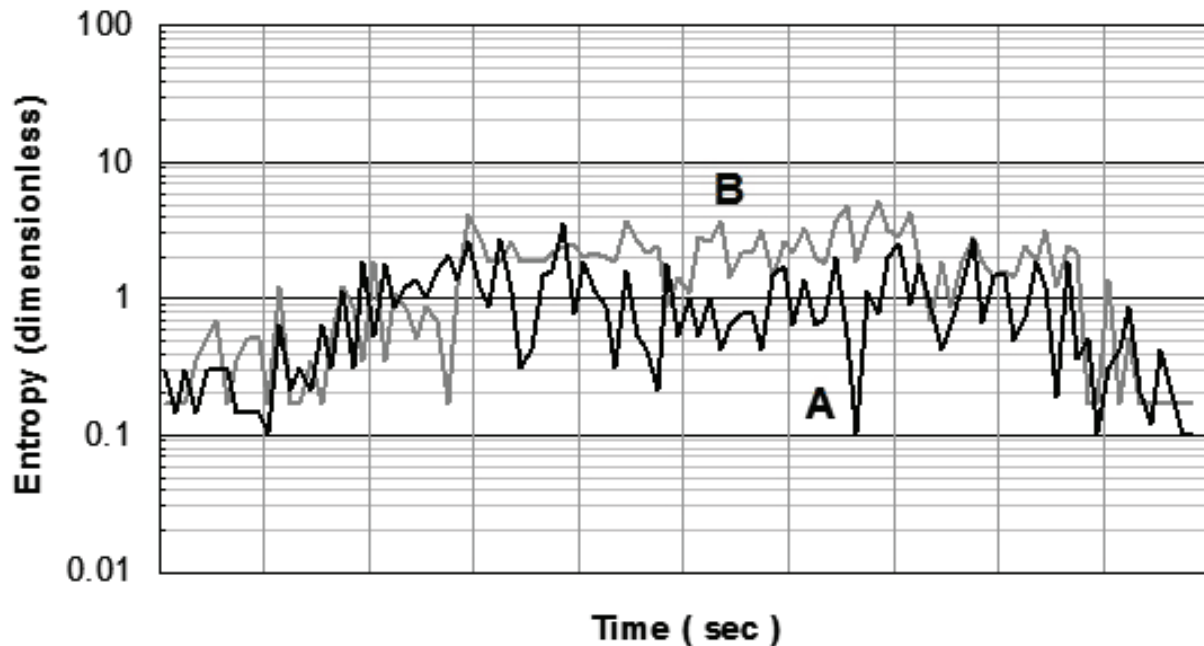One of the most commonly used surface EMG parameters which reflect paraspinal muscle fatigue during

Figure 1: Logarithmic entropy of Before (B) and After (A) muscle fatigue

Table 2: Comparison of MF and ENTR Before and After fatigue test (n =25)

Variables	Mean±SD		P value
	Before	**After**	
MU-R MF (Hz)	82.81±17.99	68.17±13.41	<0.001
MU-L MF (Hz)	81.76±15.58	70.71±15.63	<0.001
LO-R MF (Hz)	78.78±13.87	68.21±12.67	<0.001
LO-L MF (Hz)	77.91±13.65	63.73±11.59	<0.001
MU-R ENTR(-)	0.72±0.31	0.39±0.20	<0.001
MU-L ENTR(-)	0.74±0.37	0.33±0.20	<0.001
LO-R ENTR(-)	0.88±0.41	0.41±0.26	<0.001
LO-L ENTR(-)	0.81±0.40	0.39±0.25	<0.001

Table 3: Comparison of reduced percentage changes of MF and ENTR following muscle fatigue (n =25)

Variables	Mean Difference Percentage±SD		P value
	MF (Before-After)	ENTR (Before-After)	
MU-R	16.89±8.56	44.84±21.02	<0.001
MU-L	13.66±6.55	52.43±22.17	<0.001
LO-R	13.08±7.84	54.23±16.50	<0.001
LO-L	17.57±10.73	53.80±18.31	<0.001

different tasks and positions is median frequency. Fatigue causes a decrease of the frequency content of the sEMG signal usually described as a decline of the mean or median frequency of the power spectrum [8,9]. Although it is widely known that the electromyography power spectrum shifts to lower frequencies during fatiguing contraction, an opinion exists that the validity of spectral shifts in assessment of fatigue is questionable [10]. The present study was designed to evaluate the comparison between spectral and entropic measures during fatigue test of rhythmic flexion and extension by the nonlinear analysis (ENTR). Previous studies reported reliable and significantly different nonlinear measures in muscle activities prior and following fatigue [6,7,18], but because of the heterogeneity in outcome measurements and methodological limitations of previous studies [5,7,10], it is difficult to compare our findings with other literature. The findings show reduced ENTR during fatigue test with similar decrement of the MF. The current results provide some basic implications for the evaluation of muscle fatigue. Based on the significant differences of percentage changes in ENTR in comparison to MF following muscle fatigue, sensitivity of ENTR is higher than MF and shows more predictable signs. Some properties of EMG have more variation in comparison to others, for an example, RMS has little variance than duration of muscle activities. These properties are due to complexity of measurements and signal processing. ENTR has more complexity than MF so standard deviation and variance may indicated trend of increase, but percentage difference of ENTR at this research have reduced more than reduction of MF percentage difference . If a variable had more percentage changes in comparison to others, you can find it better parameter than other ones. Limitations of the current study should be addressed. We were not able to measure the movement speed of the lumbar motions. Therefore, we were not able to include movement speed as a co-variant in our statistical analyses. Another limitation is that we didn't check the ICC (Intraclass Correlation Coefficient).

Conclusion

The nonlinear (Shannon entropy) analysis is a standard measure of complexity and has been applied in different researches and fields. Findings of our study indicated that the value of the entropy was lower for subjects following fatigue than before it. And also our findings indicated that ENTR can explain sEMG changes following muscle fatigue. This result suggests MF and ENTR in healthy males seems to be good variables for fatigue index, however ENTR is more sensitive than MF. Further studies

are needed to identify the other conditions and fatigue protocols to demonstrate the existence of high correlation for ENTR among different muscles.

References

1. Ritvanen T, Zaproudina N, Nissen M, Leinonen V, Hänninen O. Dynamic surface electromyographic responses in chronic low back pain treated by traditional bone setting and conventional physical therapy. Journal of Manipulative and Physiological Therapeutics. 2007;30(1):31-7.
2. Ettema GJ, Taylor E, North JD, Kippers V. Muscle synergies at the elbow in static and oscillating isometric torque tasks with dual degrees of freedom. Motor control. 2005;9(1):59-74.
3. Farina D, Leclerc F, Arendt-Nielsen L, Buttelli O, Madeleine P. The change in spatial distribution of upper trapezius muscle activity is correlated to contraction duration. Journal of Electromyography and Kinesiology. 2008;18(1):16-25.
4. Cashaback JG, Cluff T, Potvin JR. Muscle fatigue and contraction intensity modulates the complexity of surface electromyography. Journal of Electromyography and Kinesiology. 2013;23(1):78-83.
5. Dimitrova N, Hogrel J-Y, Arabadzhiev T, Dimitrov G. Estimate of M-wave changes in human biceps brachii during continuous stimulation. Journal of Electromyography and Kinesiology. 2005;15(4):341-8.
6. Ravier P, Buttelli O, Jennane R, Couratier P. An EMG fractal indicator having different sensitivities to changes in force and muscle fatigue during voluntary static muscle contractions. Journal of Electromyography and Kinesiology. 2005;15(2):210-21.
7. Sung PS, Zurcher U, Kaufman M. Reliability difference between spectral and entropic measures of erector spinae muscle fatigability. Journal of Electromyography and Kinesiology. 2010;20(1):25-30.
8. De Luca CJ. Myoelectrical manifestations of localized muscular fatigue in humans. Critical reviews in biomedical engineering. 1983;11(4):251-79.
9. Beck TW, Stock MS, Defreitas JM. Shifts in EMG spectral power during fatiguing dynamic contractions. Muscle & Nerve. 2014;50(1):95-102.
10. Dimitrova N, Arabadzhiev T, Hogrel J-Y, Dimitrov G. Fatigue analysis of interference EMG signals obtained from biceps brachii during isometric voluntary contraction at various force levels. Journal of Electromyography and Kinesiology. 2009;19(2):252-8.
11. Slack PS, Ma X, editors. Determination of muscle fatigue using dynamically embedded signals. From: ASME 2007 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference; American Society of Mechanical Engineers.2007;5:1565-1574.
12. Coorevits P, Danneels L, Cambier D, Ramon H, Druyts H, Karlsson JS, et al. Correlations between short-time fourier-and continuous wavelet transforms in the analysis of localized back and hip muscle fatigue during isometric contractions. Journal of Electromyography and Kinesiology. 2008;18(4):637-44.
13. Talebinejad M, Chan AD, Miri A, Dansereau RM. Fractal analysis of surface electromyography signals: a novel power spectrum-based method. Journal of Electromyography and Kinesiology. 2009;19(5):840-50.

14. Kouzaki M, Fukunaga T. Frequency features of mechanomyographic signals of human soleus muscle during quiet standing. Journal of Neuroscience Methods. 2008;173(2):241-8.

15. Süüden E, Ereline J, Gapeyeva H, Pääsuke M. Low back muscle fatigue during Sorensen endurance test in patients with chronic low back pain: relationship between electromyographic spectral compression and anthropometric characteristics. Electromyography and Clinical Neurophysiology. 2007;48(3-4):185-92.

16. Dimitrov GV, Arabadzhiev TI, Mileva KN, Bowtell JL, Crichton N, Dimitrova NA. Muscle fatigue during dynamic contractions assessed by new spectral indices. Medicine and Science in sports and exercise. 2006;38(11):1971.

17. Webber C, Schmidt M, Walsh J. Influence of isometric loading on biceps EMG dynamics as assessed by linear and nonlinear tools. Journal of Applied Physiology. 1995;78(3):814-22.

18. Talebinejad M, Chan AD, Miri A. Multiplicative multi-fractal modeling of electromyography signals for discerning neuropathic conditions. Journal of Electromyography and Kinesiology. 2010;20(6):1244-8.

19. Eckmann J-P, Kamphorst SO, Ruelle D. Recurrence plots of dynamical systems. Europhys Lett. 1987;4(9):973-7.

20. Sung PS, Zurcher U, Kaufman M. Comparison of spectral and entropic measures for surface electromyography time series: a pilot study. Journal of Rehabilitation Research and Development. 2007;44(4):599.

21. Costa M, Goldberger AL, Peng C-K. Multiscale entropy analysis of biological signals. Physical review E. 2005;71(2):021906.

22. Allen PA, Murphy MD, Kaufman M, Groth KE, Begovic A. Age differences in central (semantic) and peripheral processing: The importance of considering both response times and errors. The Journals of Gerontology Series B: Psychological Sciences and Social Sciences. 2004;59(5):P210-P9.

23. Caplin A, Dean M. Behavioral implications of rational inattention with shannon entropy. National Bureau of Economic Research, 2013.