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Correlations between short-time Fourier- and continuous wavelet transforms in the analysis of localized back and hip muscle fatigue during isometric contractions

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Abstract

The aims of the current study were to examine the stationarities of surface electromyographic (EMG) signals obtained from eight bilateral back and hip muscles during a modified Biering-Sørensen test, and to investigate whether short-time Fourier (STFT) and continuous wavelet transforms (CWT) provided similar information with regard to EMG spectral parameters in the analysis of localized muscle fatigue. Twenty healthy subjects participated in the study after giving their informed consent. Reverse arrangement tests showed that 91.6% of the EMG signal epochs demonstrated no significant trends (all $p > 0.05$), meaning 91.6% of the EMG signal epochs could be considered as stationary signals. Pearson correlation coefficients showed that STFT and CWT in general provide similar information with respect to the EMG spectral variables during isometric back extensions, and as a consequence STFT can still be used.

Keywords: Electromyography; Wavelets; Fourier; Isometric contraction; Muscle fatigue; Median frequency

1. Introduction

Chronic low back pain patients (LBP) have demonstrated excessively fatigable back muscles (Biering-Sørensen, 1984; Chok et al., 1999; Mayer et al., 1989; Roy et al., 1989; Tsuboi et al., 1994). The modified Biering-Sørensen test is a widely used test for evaluating back muscle fatigue (Albert et al., 2004; Bradl et al., 2005; Eguchi, 2004; Mannion and Dolan, 1994; Mannion et al., 1998; Sung et al., 2005; Suter and Lindsay, 2001). It has been shown that the Biering-Sørensen test was able to discriminate between patients with chronic LBP and healthy persons (Latimer et al., 1999; Luoto et al., 1995; Roy et al., 1989). Many studies have used surface electromyography (EMG) to study back muscle fatigue. The electrical manifestations of muscle fatigue, often labeled as ‘localized muscle fatigue’, have been quantified by both EMG time domain (amplitude) as well as EMG frequency domain parameters (mean and/or median power frequency). In the analysis of localized back muscle fatigue, it has been shown that fatigue generally causes an increase in the EMG amplitude and a decrease in the mean and/or median power frequency (Larivière et al., 2002; Mannion et al., 1997; Mannion and Dolan, 1994; Mannion et al., 1998; Merletti et al., 1992). Parameters derived from the EMG power spectrum are less dependent on the force level of the muscle

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compared to amplitude parameters, and are therefore more sensitive to the myoelectric manifestations of muscle fatigue (Potvin and Bent, 1997).

Traditionally, Fourier transforms have been used to derive the EMG spectral variables (Pope et al., 2000; Sparto et al., 1999). These Fourier transforms have the limitation that they require a stationary signal (Beck et al., 2005; Karlsson et al., 1999, 2000; Knaflitz and Bonato, 1999). Opinions agree that EMG signals obtained during dynamic contractions are non-stationary due to changes in muscle length, muscle force, velocity of movement, and location of the electrodes with respect to the active muscle fibers (Knaflitz and Bonato, 1999; Roy et al., 1998). With regard to isometric contractions, studies have mentioned that the EMG signal obtained during constant-force isometric contractions can be seen as wide-sense stationary (i.e. first and second statistical moments of the stochastic process do not change over time) over time epochs ranging from 0.5 to 2 s, depending on the exerted force and on the muscles' properties (Karlsson et al., 1999, 2000; Knaflitz and Bonato, 1999). More precisely, Merletti et al. mentioned that the myoelectric signal can be seen as wide-sense stationary during short contractions (20–40 s) at low level contractions (20–30% of maximal voluntary contraction (MVC)), and for a period of 0.5–1.5 s of contractions of higher levels (50–80% MVC) (Merletti et al., 1992). In order to overcome the stationarity problem when using Fourier transforms, it is common practice to divide the raw EMG signals into blocks of short duration where the wide-sense stationarity holds (Karlsson et al., 2000), the so called short-time Fourier transform (STFT). The STFT avoids the problem of stationarity, but has restrictions due to the time–frequency resolution (Beck et al., 2005; Hostens et al., 2004). Because STFT uses a fixed time resolution, the corresponding frequency resolution is also fixed (Beck et al., 2005; Karlsson et al., 2000; Ng et al., 1997). Therefore, small window widths allow good time resolution but poor frequency resolution, and longer window widths allow good frequency resolution but poor time resolution (Beck et al., 2005; Karlsson et al., 1999).

In the past years, other time–frequency methods such as wavelets have been used to overcome the problems mentioned above (Hostens et al., 2004; Karlsson et al., 1999, 2000). The advantage of wavelets over STFT, is that wavelet transforms vary the time–frequency aspect ratio, producing good frequency localization at low frequencies (long time windows), and good time localization at high frequencies (short time windows) (Hostens et al., 2004). Although it is frequently mentioned that Fourier transforms cannot be used in case of nonstationary signals (because the basic assumption of stationarity is violated), very little evidence is presented in the literature how much error is actually introduced when nonstationary signals are indeed processed with Fourier based methods to obtain a spectral analysis. In a study of Houtveen et al., the authors compared Fourier- and wavelet based methods to calculate the power spectra of heart rate variability data. High correlation coefficients (>0.95) and small differences (<1%) were demonstrated between power spectra of both methods (with the differences being larger for nonstationary signals) (Houtveen and Molenaar, 2001). However, the authors mentioned they were nonetheless convinced that the wavelet method – and not the Fourier based analysis – is the theoretically valid method to use with nonstationary data (Houtveen and Molenaar, 2001). Zhang et al. have used a model to simulate the Doppler blood flow signal of the normal carotid artery. The authors demonstrated that the wavelet based spectra better fitted the theoretical spectra than did Fourier methods. Furthermore, it was demonstrated that larger errors were introduced when the short-time Fourier approach was used compared to wavelets (Zhang et al., 2003). The authors concluded that wavelets are suitable for analyzing nonstationary signals like Doppler blood flow signals (Zhang et al., 2003). Karlsson et al. have compared – among other time–frequency representation methods – wavelets with short-time Fourier transforms in obtaining the EMG power spectra in both stationary and non-stationary signals, simulated and real EMG signals, and in static and dynamic contractions (Karlsson et al., 1999, 2000). In the case of real EMG recordings during sustained isometric muscle contractions, the authors demonstrated (based on bootstrap estimation of the standard errors of spectral parameters) that wavelets performed slightly better than short-time Fourier transforms. High correlation coefficients between wavelet – and Fourier based mean power frequency parameters were demonstrated during these static contractions (Karlsson et al., 1999). When assessing the differences between the two time–frequency methods in non-stationary synthesized EMG signals, the authors demonstrated lower relative errors when wavelets were used compared to short-time Fourier transforms (Karlsson et al., 2000). In real EMG recordings during dynamic contractions, wavelets yielded smoother and less noisy estimates than short-time Fourier transforms (Karlsson et al., 2000). Although – based on the studies mentioned above – wavelets may be preferred over Fourier transforms, other studies have also demonstrated that short-time Fourier transforms can still be used (even in non-stationary conditions). MacIsaac et al. have mentioned that short-time Fourier transforms are suitable for evaluating muscle fatigue during dynamic contractions because this method was able to demonstrate a decreasing mean power frequency during the fatiguing contractions (MacIsaac et al., 2001). Beck et al. demonstrated very high correlation coefficients between wavelet – and Fourier based methods in assessing EMG spectral variables during non-stationary isokinetic contractions (Beck et al., 2005).

A limited number of studies have investigated the EMG signal stationarity, thereby focussing on the analysis of EMG signals from forearm muscles (such as the biceps brachii muscles) during isometric step and ramp (Bilodeau et al., 1997, 1992), dynamic (Shankar et al., 1989) and isokinetic contractions (Beck et al., 2005). Because different muscles can demonstrate different spectral characteristics (e.g. due to differences in fibre type composition) (Kumar