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Discrete wavelet transform analysis of surface electromyography for the fatigue assessment of neck and shoulder muscles

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ABSTRACT

Assessment of neuromuscular fatigue is essential for early detection and prevention of risks associated with work-related musculoskeletal disorders. In recent years, discrete wavelet transform (DWT) of surface electromyography (SEMG) has been used to evaluate muscle fatigue, especially during dynamic contractions when the SEMG signal is non-stationary. However, its application to the assessment of work-related neck and shoulder muscle fatigue is not well established. Therefore, the purpose of this study was to establish DWT analysis as a suitable method to conduct quantitative assessment of neck and shoulder muscle fatigue under dynamic repetitive conditions. Ten human participants performed 40 min of fatiguing repetitive arm and neck exertions while SEMG data from the upper trapezius and sternocleidomastoid muscles were recorded. The ten of the most commonly used wavelet functions were used to conduct the DWT analysis. Spectral changes estimated using power of wavelet coefficients in the 12–23 Hz frequency band showed the highest sensitivity to fatigue induced by the dynamic repetitive exertions. Although most of the wavelet functions tested in this study reasonably demonstrated the expected power trend with fatigue development and recovery, the overall performance of the "Rbio3.1" wavelet in terms of power estimation and statistical significance was better than the remaining nine wavelets.

1. Introduction

Work-related repetitive upper extremity exertions are a known cause of neck and shoulder musculoskeletal disorders (MSDs). In 2010, repetitive upper extremity exertions resulted in the highest number (median = 24) of days away from the work compared to all other types of exertions combined (median = 8) (BLS, 2011). The overuse of muscles, nerves, and/or joints caused by repetitive movements leads to muscle fatigue which is believed to be the precursor to most of the inflammatory-type neck and shoulder MSDs (Larsson et al., 2007). Therefore, accurate methods for muscle fatigue assessment are essential for the early detection and prevention of MSDs associated with repetitive upper extremity exertions.

A number of methods are used for the assessment of muscle fatigue generated by the work-related demands. Some of the most commonly used methods include evaluation of maximum voluntary contraction (Newham et al., 1991), endurance time (Garg et al., 2002), metabolite concentrations (Cady et al., 1989), perceived effort (Ahsberg et al., 2000), and subjective discomfort ratings (Öberg et al., 1994). Most of these methods are typically used in the evaluation of fatigue generated by heavy or sustained static exertions (Vøllestad, 1997) and may not be receptive to the subtle fatigue-induced physiological changes caused by sub-maximal repetitive exertions. The muscle action potential characteristics are likely to change in response to the neuromuscular fatigue caused bysub-maximal exertions. The traditional methods used to evaluate changes in the action potential typically rely on metrics such as changes in the mean/median of the frequency spectrum obtained using fast Fourier transform (FFT) of muscle electromyography (Potvin, 1997). The FFT based estimation accurately quantifies the signal frequency content, i.e. how much of each frequency exists in the signal spectrum, but timing information, i.e. when a particular frequency component takes place in time, cannot be determined using the FFT method. For a stationary signal (all frequency components exist at all times), the timing information may be extraneous and shift in the power spectrum frequencies provides reliable indication of the muscle fatigue (Hostens et al., 2004). However, under repetitive dynamic conditions, the spectral changes of the non-stationary EMG signal estimated by FFT may not indicate the muscle fatigue accurately (Moshou et al., 2005). In such cases, the short time Fourier transform (STFT) is used, which implements window sizes of variable widths so that the stationary requirement is met. However, the window size approximation can constrain the signal spectrum estimation. For example, a short window size in STFT provides better time resolution, but

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poor frequency resolution; while a relatively long window size provides better frequency resolution but poor time resolution (Hostens et al., 2004).

The discrete wavelet transform (DWT) provides a potential solution to this time and frequency resolution issue because of its ability to simultaneously elucidate local spectral and temporal information from a signal (Samar et al., 1999). It acts as a "mathematical microscope" in which one can observe different parts of the signal by adjusting the focus. Another advantage of DWT is the availability of various orthogonal wavelet functions that allow the most appropriate one to be chosen for the signal under investigation (Polikar, 2006). This is in contrast to the FFT analysis which is restricted to one feature morphology: the sinusoid. While sinusoid functions are useful in analyzing periodic and time-invariable phenomena, wavelets are well suited for the analysis of transient, time varying signals (Daubechies, 1990). A few previous studies have clearly stated that the wavelet transform is a more reliable method for the evaluation of fatigue induced spectral changes than Fourier transform, especially when the signal under investigation is non-stationary (Hua et al., 2007; Vukova et al., 2008).

Despite suitability of DWT for spectral analysis of non-stationary EMG signals, there is a lack of available data in the literature concerning its application for evaluation of muscle fatigue generated by work-related repetitive exertions. Therefore, the purpose of this study was to establish DWT analysis as a suitable method to conduct quantitative assessment of neck and shoulder muscle fatigue generated by repetitive exertions. The specific objectives of this study were to: (1) compare commonly used wavelet functions and identify the most appropriate one for analyzing neuromuscular fatigue of neck and shoulder muscles generated by repetitive exertions; (2) identify the frequency bands that show characteristic changes with the development of fatigue and recovery.

2. Methods

2.1. Protocol overview

In this study, ten of the most commonly used wavelet functions were used to analyze the SEMG data using discrete wavelet transform (DWT) analysis. The SEMG data were recorded during repetitive upper extremity exertions performed under normal and fatigued conditions. The neuromuscular fatigue was generated experimentally using repetitive upper extremity exertions performed over two 20 min sessions, with a 5 min break between the sessions. The activity of major neck and shoulder muscles responsible for these exertions i.e., right upper trapezius and left sternocleidomastoid muscles (contra-lateral to the direction of head rotation), were recorded using surface electromyography (SEMG). Seven levels of decomposition were used to compute power of the signal in different frequency bands. Power trends were statistically compared to identify wavelet functions and the frequency bands that are most sensitive to the fatigue induced spectral changes.

2.2. Participants

A convenient sample of ten healthy engineering graduate and undergraduate male students was used for data collection. The average age, weight, and height of the participants were 27(4.8) years, 71.12(9.30) kg, and 170.2(11.1) cm, respectively. The primary inclusion criteria used in this study required that the participants were free from any type of musculoskeletal disorders and had no history of neck and shoulder injury or notable neck pain. The Physical Activity Readiness Questionnaire (PAR-Q, Canadian Society for Exercise Physiology) was used to screen participants for cardiac and other health problems (e.g., dizziness, chest pain, heart trouble). Participants who met the inclusion criteria were asked to read and sign a consent form approved by the local Institutional Review Board.

2.3. Apparatus/tools

2.3.1. Electromyography (EMG) system

A 16-channel telemetry EMG system consisting of a Telemyo 2400T wireless transmitter, pre-amplified lead wires, and disposable, self-adhesive Ag/AgCl snap electrodes was used to collect SEMG data. The bipolar Ag/AgCl pre-gelled surface electrodes (1 cm diameter, inter-electrode distance is 2 cm) connect to the Telemyo 2400T transmitter via pre-amplified lead wires. The pre-amplifier on the lead wires have CMRR > 100 dB, Input Impedance > 100 MΩ, and base gain of 500. The range of the band pass filter was 10–500 Hz (Noraxon, 2011). The frequency of EMG data acquisition was set at 1500 Hz.

2.3.2. Workstation

A custom-built workstation was used to simulate repetitive upper extremity exertions. This workstation consists of two adjustable orthogonally-placed work surfaces (Fig. 1b). If a participant is facing surface 1, then surface 2 is to the right of the participant. Thirty small cylindrical containers (diameter = 3.0 cm; height = 5.0 cm; weight = 50 g) were used to perform the repetitive upper extremity exertions. A stand containing these cylinders was placed on surface 1, which was adjusted to the participant's fingertip height. The height of surface 2 was adjusted to the standing eye height of the participant.

2.4. Experimental protocol

Upon arriving at the laboratory, each participant was introduced to the equipment, data collection procedures, and specifics of the experimental tasks. The demographics and anthropometric measures of the participant were recorded and they were then subsequently prepared for SEMG data collection. SEMG from the left sternocleidomastoid muscle was recorded by placing an electrode along a line drawn from the sternal notch to the mastoid process, at 1/3 the distance from the mastoid process (Nimbarte et al., 2010, 2012). SEMG from the right upper trapezius muscle was recorded by placing an electrode along a line joining the acromion and C7, at 1/3 the distance from the acromion process (Nimbarte et al., 2010, 2012). The skin underneath the anatomical landmarks was shaved (if needed), and cleaned with 70% alcohol, prior to the placement of the SEMG electrodes.

Next, the participant performed repetitive upper extremity exertions to manually transfer 30 cylindrical containers from surface 1 to surface 2. Once all 30 containers have been moved from surface 1 to surface 2 (stocking operation), the participant began the un-stocking operation, i.e. transferring the containers back to surface 1 from surface 2. These exertions closely replicate the top shelf stocking and unstocking operations performed by a super market grocery clerk (Fig. 1a). Each motion involved 90° of flexion and abduction of the upper arm, 60–90° of head-neck rotation and 10–20° of head-neck extension. Stocking and unstocking operations were performed continuously for a duration of 20 min (session 1). A rest period of 5 min was provided at the end of session 1. After the rest period, the participant continued the same stocking and unstocking operation for another 20 min (session 2).

SEMG data was recorded continuously during sessions 1 and 2. In addition, at the end of each session, the participant was asked to report discomfort in the right shoulder region and the left anterior neck region using Borg's subjective rating scale (Borg, 1998). The