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Effect of fatigue on the stationarity of surface electromyography signals

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ABSTRACT

The estimation of muscle fatigue using surface electromyography (SEMG) is of high relevance to evaluate ergonomic risk factors in the occupational settings. Signal stationarity plays an important role while selecting appropriate SEMG signal processing method for fatigue evaluation. The Fourier algorithm based signal processing methods (mean or median frequency of power spectrum) rely on the assumption that the signal under investigation is stationary. Stationarity of SEMG signals and its association with fatigue is rarely studied in the ergonomics literature. Therefore, this study was aimed at understanding the effect of fatigue on the stationarity of the SEMG data. Ten participants performed 40 min of fatiguing upper extremity exertions and SEMG data were recorded from the right upper trapezius muscle. The SEMG data recorded under static and dynamic conditions at the beginning and at the end of fatiguing exertions were used in the analysis. The stationarity analysis was performed for five window sizes of 128, 256, 512, 768 and 1024 ms using modified reverse arrangement test. The results showed that the muscle fatigue reduced the stationarity of the SEMG signal under static and dynamic conditions. The relationship between the muscle fatigue and the stationarity of the SEMG signal was found to be significant at the window size of 512 ms. A significantly higher fatigue related decrease in the stationarity was observed during dynamic exertions compared to the static exertions.

Relevance to industry: The findings from the current study illustrate that the stationarity of SEMG signals could be used to quantify muscle fatigue under static and dynamic task conditions. These findings are useful to the ergonomic practitioners in conducting muscle fatigue estimation using SEMG.

1. Introduction

Neuromuscular fatigue is believed to be one of the precursors of work-related musculoskeletal disorders (MSDs) (Armstrong et al., 1993) and therefore precise fatigue estimation methods are essential for MSD prevention. Among various methods that are used to estimate the neuromuscular fatigue, surface electromyography (SEMG) is a preferred method by many ergonomists.

The changes in the frequency spectrum of the SEMG signal, i.e., a shift in the mean or median frequencies toward lower values or a change in the power of the low and high frequency components, are used as the common indicators of muscle fatigue (Chowdhury et al., 2013; Shankar et al., 1989; Kumar and Narayan, 1999; Pau et al., 2014; Nussbaum, 2009).

The fast Fourier transform (FFT) or discrete Fourier transform (DFT) (Beck et al., 2006) algorithms are used to study the frequency spectrum of SEMG signals. These algorithms assume that the signal under investigation is stationary (Oppenheim et al., 1989; Bilodeau et al., 1997). A SEMG signal is said to be stationary if the average, variance, and frequency contents of the signal do not alter over time (Oppenheim et al., 1989; Blanco et al., 1995; Bendat and Piersol, 2000). In the case of non-stationary SEMG signals, the set of samples are statistically dependent and the mean, variance and frequency content of the signals change over time (Shwedyk et al., 1977; Beck et al., 2005).

Literature on the stationarity of SEMG signal is limited to how it is affected by selection of different window sizes. Cho and Kim (2012) reported that the stationarity level of the SEMG signal is significantly affected by the choice of window size. The authors observed a higher stationary level at a window size of 750 ms compared to the window sizes of 250, 500, 1000 and 2000 ms for

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the erector spinae muscles during 0%, 25% and 50% MVC levels. In another study, Waly et al. (2003). investigated the effect of window sizes (64, 128, 256, 512, 1024, 2048, and 4096 ms) on the frequency characteristics of the SEMG signal during sustained isometric exertions performed at 25%, 50%, and 100% MVC levels. The authors recommended that a window size smaller than 250 ms should be avoided in order to eliminate high variability in the spectral estimation of the SEMG data. For the window size of 500–1000 ms, the SEMG signal recorded from the bicep-brachii muscle during isometric exertions at 50% MVC was reported to be stationary by Inbar and Noujaim (1984).

In addition to the window size, fatigue, can also affect signal stationarity due to the time-dependent variation in the SEMG produced by altered motor unit recruitment pattern. However, no previous study has evaluated relationship between SEMG signal stationarity and muscle fatigue due to work-related exertions. This study was aimed at understanding the effect of muscle fatigue on the stationarity of the SEMG signal. It was hypothesized that the fatigue would affect the stationarity of the SEMG signal. The reverse arrangement test, and modified reverse arrangement test have been used in the past to evaluate the stationarity of the SEMG signals (Beck et al., 2006; Cho and Kim, 2012). Cho and Kim (2012) suggested that modified reverse arrangement test as the modified type of reverse arrangement test, was more conservative method in judging SEMG signal stationarity. Thus, the modified reverse arrangement test was used to study the stationarity of the SEMG signals in this study.

2. Methods

2.1. Approach

A lab-based experiment was performed to generate neuromuscular fatigue by simulating arm exertions. The exertions involved repetitive transferring of small loads from fingertip height to eye-height while the subject was in a standing position. These exertions required repetitive elevation and abduction of the right shoulder and arm. The SEMG data were recorded from the right upper trapezius muscle.

2.2. Participants

Ten healthy male subjects were recruited for the data collection. The average age, mass, and height of the subjects were 27 (±4.8) years, 71.1 (±9.3) kg, and 170.2 (±11.1) cm, respectively. The subjects were free from any type of musculoskeletal disorders and had no history of neck and shoulder injury. Before data collection, the experimental procedures were explained to the subjects, and their signatures were obtained on the consent forms approved by the local institutional review board.

2.3. Apparatus/tools

2.3.1. Electromyography (EMG) system

The EMG system used in this study consist of a 16-channel wireless transmitter (Telemyo 2400T), pre-amplified lead wires (CMRR>100 dB and input impedance > 100 MΩ), and disposable, self-adhesive Ag/AgCl snap electrodes (1 cm diameter, interelectrode distance is 2 cm) (Noraxon, 2011). The bipolar electrodes connect to one end of the pre-amplified lead wires and the other end of the lead wires connect with the wireless transmitter. The SEMG data was sampled at a frequency of 1500 Hz.

2.3.2. Workstation

A custom-built workstation was used to perform repetitive arm exertions. This workstation consists of two adjustable work surfaces placed orthogonally with respect to the participant (Fig. 1). Thirty small cylindrical containers (diameter = 3.0 cm; height = 5.08 cm; weight = 50 g) were used to perform the repetitive exertions.

2.4. Experimental design

A two-factor experimental design was used. Factor 1, fatigue was treated at two fixed levels (non-fatigued and fatigued). As noted, repetitive exertions were used to induce fatigue. The muscle activity data recorded prior to or at the beginning of the physical exertions were treated as “non-fatigued” condition. The muscle activity data recorded at the end of the physical exertions were treated as “fatigued” condition. Factor 2, type of exertion was also treated at two fixed levels (static and dynamic). The SEMG data recorded during a static T-pose (90 degrees of arm abduction in frontal plane) prior to and after the completion of physical exertions were treated as the “static or isometric” condition. The muscle activity data recorded during repetitive arm exertions at the beginning and at the end of repetitive arm exertion were treated as the “dynamic” condition (Fig. 2).

2.5. Data collection

First, the experimental set-up, equipment, and data collection procedures were explained to the participants. Subsequently, the following stepwise procedure was used to collect the experimental data.

2.5.1. SEMG data collection preparation

The SEMG data from the right upper trapezius muscle were recorded by placing an electrode along a line joining the acromion and C7, at 1/3 the distance from the acromion process. Prior to the placement of the SEMG electrodes, the skin of the anatomical landmarks was shaved, abraded and cleaned with 70% alcohol.

2.5.2. Experimental procedure

Once the participants were instrumented with the surface electrodes, they performed three 10 s isometric reference exertions (90 degrees of arm abduction in frontal plane) (Fig. 2). Next, the participants performed repetitive stocking and un-stocking operations using the custom-built workstation (Figs. 1 and 2). The participant stood at a comfortable distance from the surface 1 and 2. The heights of the surface 1 and 2 were adjusted to the participant's fingertip and eye heights, respectively. During stocking operation, the participants manually transferred 30 cylindrical containers from surface 1 to surface 2 (Figs. 1 and 2). During unstocking operation, the containers were transferred back to surface 1. The stocking and unstocking operations were performed continuously for 20 min (session 1) followed by a rest period of 5 min. After the rest period, participants continued the same stocking and un-stocking operations for another 20 min (session 2). The SEMG data were recorded continuously during sessions 1 and 2. At the end of session 2, three repetitions of isometric reference exertions were collected. The participants were provided at least 1.5 min of rest period between any two isometric reference exertions as well as prior to the repetitive dynamic exertions. In addition, at the end of each session, subjective discomfort data in the right shoulder region were recorded using Borg's scale (Borg, 1982).

2.6. Data processing

The SEMG signals were processed using a custom-built Matlab script in MATLAB (R2011a, The Math Works Inc.) software. The