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Proceedings of the Human Factors and Ergonomics Society Annual Meeting 2012 56: 1145
DOI: 10.1177/1071181312561249

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Assessment of neck and shoulder muscle fatigue using discrete wavelet transforms of surface electromyography

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Objective assessment of neuromuscular fatigue is important for the early detection and prevention of risks of work-related musculoskeletal disorders (MSDs). Although, in recent years, a number of researchers have used discrete wavelet transforms (DWT) of surface electromyography (SEMG) to evaluate muscle fatigue, its application to neck and shoulder muscle fatigue assessment 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 caused by dynamic exertions. Six human participants performed 40 minutes of fatiguing repetitive arm and neck exertions. SEMG data from the right upper trapezius and left sternocleidomastoid muscles were recorded. Six most commonly used orthogonal wavelet functions were used to conduct DWT analysis. With the development of fatigue for most of the wavelet functions a significant increase in the power in the lower frequency bands of 12-23Hz and 23-46Hz was observed. Bior 3.1 wavelet showed the highest power, statistically consistent and meaningful power trend and the highest overall power contrast compared to the remaining five wavelets tested in this study.

INTRODUCTION

According to U.S. Bureau of Labor Statistics (BLS, 2011), there were total 346,400 cases of musculoskeletal disorders (MSDs) in 2010. Among these cases, neck and shoulder MSDs accounted for 16,980 and 87,040 cases, respectively, with 8 and 21 median days away from work compared to 8 days away from work for all cases combined. In the recent data published by the Bone and Joint Decade on Neck Pain Task Force an annual prevalence of 30% to 50% for neck pain amid the general adult population was reported (Côté et al., 2008). Among the various work-related factors that are identified as the risk factors of neck/shoulder work-related MSDs, evidence for a causal relationship between repetitive arm and neck exertions and neck/shoulder WMSDs is mounting in the literature (Côté et al., 2008). Overuse of muscles, nerves, and/or joints caused by repetitive movement leads to muscle fatigue, which is believed to be the precursor of MSDs (Larsson, Sogaard, & Rosendal, 2007) and, therefore, quantitative assessment of muscle fatigue is essential for early detection and prevention of risks of work-related MSDs.

A number of objective (strength, metabolite concentration, etc.) as well as subjective (perceived effort, discomfort ratings) assessment methods are being used for muscle fatigue assessment (Vøllestad, 1997). Most of these methods are sensitive to fatigue generated by high force or static sustained exertions, but, these methods are not receptive to the subtle physiological changes caused by sub-maximal repetitive exertions (Bonato, Gagliati, & Knaflitz, 1996).

Surface Electromyography (SEMG) is a non-invasive and fairly accurate tool for continuous monitoring of muscle fatigue during a physical activity. However, traditional methods for evaluating muscle fatigue using SEMG signals have typically relied on metrics such as changes in the mean/median of frequency spectrum obtained using fast Fourier transform (FFT) (Potvin, 1997) . Analysis using FFT algorithm assumes that the signal is stationary. Under repetitive dynamic conditions the SEMG signal is non-stationary and therefore spectral changes estimated by FFT may not provide reliable assessment of muscle fatigue (Moshou, Hostens, Papaioannou, & Ramon, 2005). Short time Fourier transform (STFT) provides a possible solution to this problem, but, signal spectrum estimated by STFT is constrained by window size approximation. A short window size in STFT provides better time resolution, but poor frequency resolution; while a relatively long window size provides better frequency resolution but poor time resolution (Hostens, Seghers, Spaepen, & Ramon, 2004).

Analysis using discrete wavelet transform (DWT) provides a potential solution to this time and frequency resolution issue. DWT based analysis acts as a "mathematical microscope" in which one can observe different parts of the signal by just adjusting the focus. Another key advantage of DWT is the variety of wavelet functions available, thus allowing the most appropriate wavelet functions to be chosen for the signal under investigation. This is in contrast to Fourier analysis which is restricted to one feature morphology: the sinusoid.

Although, in recent years a number of studies have used DWT for evaluating muscle fatigue using SEMG (Kumar, Pah, & Bradley, 2003; Moshou et al., 2005), its application to neck and shoulder muscle fatigue assessment is not well established. Therefore, the purpose of this study is to establish wavelet analysis as a suitable method to conduct quantitative assessment of neck and shoulder muscle fatigue caused by repetitive exertions.

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METHODS

Approach

Material handling task consisting of repetitive stocking and un-stocking of small objects was used to generate neuromuscular fatigue in the lab setting. The stocking and un-stocking operations involve repetitive arm and neck exertions. The electrical activity of right upper trapezius and left sternocleidomastoid muscles was recorded using SEMG. Muscle fatigue generated by the repetitive exertion was evaluated using DWT analysis. Six most commonly used orthogonal wavelet functions were used to perform the DWT analysis.

Participants

Six healthy male participants (age 24.9±4.1 years; weight 74.54±9.30 Kg; height178.6±6.6 cm) with no known MSDs and no history of neck and shoulder injury or notable neck or shoulder pain participated in this study. 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). All the participants signed consent form approved by the local Institutional Review Board prior to their participation in this study.

Equipment

Electromyography system. A 16 channel portable SEMG system (Noraxon Inc., Arizona, USA), with pre-amplified lead wires (gain 500, band pass 10-1000 Hz, CMRR > 100 dB, input impedance >100 MΩ), and disposable, pre-gelled Ag/AgCl surface electrodes (1cm diameter, 2cm inter-electrode distance) were used to collect SEMG data (Noraxon, 2011). The sampling frequency of SEMG data acquisition was set at 1500 Hz.

Workstation. A custom-built standing workstation was designed to simulate material handling task. This workstation consists of two adjustable orthogonally-placed work surfaces (Figure 1(a)). Thirty small cylindrical weights (diameter = 3.2 cm; height = 5.0 cm; weight = 50.0 grams) were used to perform the repetitive stocking and un-stocking exertions. A stand containing these cylinders was placed on the surface 1, which was adjusted to the fingertip height. Height of the surface 2 was adjusted to the standing eye height.

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 (age, height, and weight) of the participant were recorded. SEMG data from the sternocleidomastoid muscle was recorded by placing an electrode along a line drawn from the sternal notch to the mastoid process, at 1/3 the length of the line from the mastoid process (Falla, Dall'Alba, Rainoldi, Merletti, & Jull, 2002). For the upper trapezius muscle, electrode was placed at a location along a line joining the acromion process and C7, at 1/3rd the distance from the acromion process (Farina, Madeleine, Graven-Nielsen, Merletti, & Arendt-Nielsen, 2002). The skin over the anatomical landmarks was shaved, and cleaned with alcohol prior to the electrodes placement.

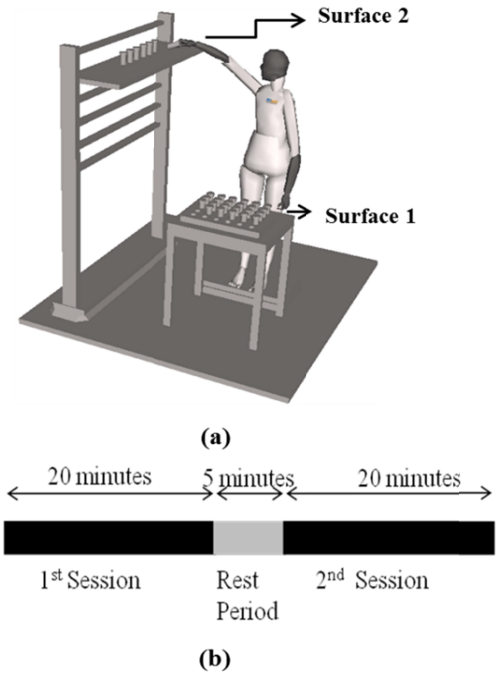

Figure 1: (a) Custom-built standing workstation used in this study (b) Experimental time distribution.

Next, the participants performed material handling task by manually transferring 30 cylindrical boxes between the stand on the surface 1 and the surface 2. At first, the boxes were transferred from surface 1 to surface 2 (stocking operation) followed by the un-stocking operation i.e. transferring the boxes back to the stand on the surface 1 from the surface 2. These stocking and unstocking operations were continuously performed by the participants for a duration of 20 minutes (1st session) followed by a rest period of 5 minutes. After the rest period participants continued the same exertions for another 20 minutes (2nd session). At the end of each session, the participants were asked to report discomfort in the right upper trapezius and left sternocleidomastoid muscles using a 10 point Borg's subjective rating scale (Table 1).

Table 1: Borg's scale of subjective discomfort rating.

Number	Severity
1	Nothing at all
2	Just Noticeable
3	Very Slight
4	Slight
5	Slight Moderate
6	Moderate
7	Some difficulty
8	Moderate Severe
9	Severe
10	Very Severe

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Data processing

The SEMG data from the 5 repetitions during the stocking operations at the beginning and the end of sessions 1 and 2 were used for performing DWT analysis. The procedure for signal decomposition uses a high-pass filter to obtain high frequency components, called detail coefficients (CD) and a low-pass filter to obtain low frequency components, called approximation coefficients (CA) (Figure 2). The process of decomposition can be continued until two samples are left. Previous DWT based fatigue assessment studies reported charateristics changes in the 5-30 Hz frequency band with the onset and development of fatigue (Dolan, Mannion, & Adams, 1995; Kumar et al., 2003). Therefore, in this study, seven levels of decomposition were used to perform DWT analysis. Based on the Nyquist's theory (Parameswariah & Cox, 2002), for sampling frequency of 1500 Hz, the maximum signal frequency is 750 Hz. At different decomposition level (L), relationship between sampling frequency (f_s) and frequency bandwidth (B) is given by following equation (Cong et al., 2010):

$$B = f_s/2\text{^}(L+1) \quad (1)$$

Wavelet toolbox of Matlab (R2011a) was used to conduct the DWT analysis. The original SEMG signal X decomposed to seven levels could be expressed using the following vector:

$$X = (CA7, CD7, CD6, CD5, CD4, CD3, CD2, CD1) \quad (2)$$

Where CA7 represent the approximation coefficients at the 7th decomposition level and CD1 to CD7 are the detail coefficients at decomposition levels 1 to 7, respectively (Figure 2).

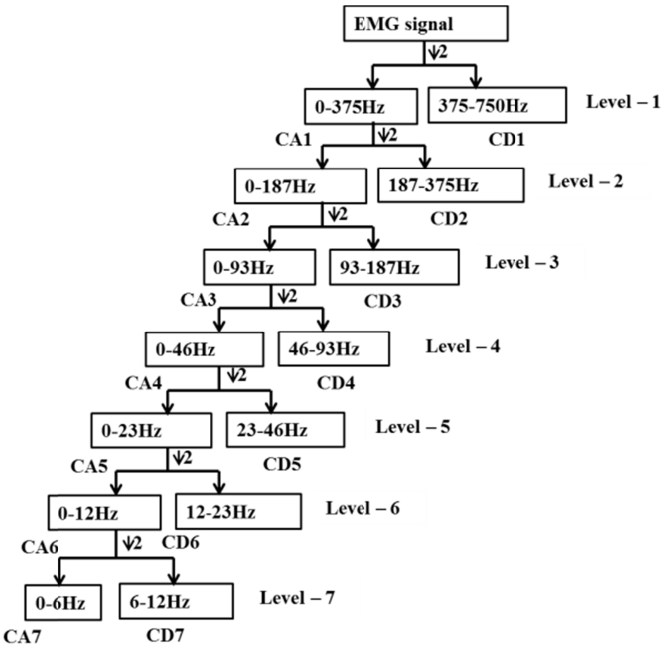

Figure 2: DWT based decomposition of the SEMG signal and the corresponding frequency bands.

The following most commonly used six orthogonal wavelet functions were used to conduct DWT analysis:

- Symlet 5 (Sym5),
- Symlet 7 (Sym7),
- Discret Meyer (Dmey),
- BiorSplines 1.3 (Bior1.3),
- BiorSplines 3.1 (Bior3.1)
- Daubechies 2 (Db2).

Data from each repetition was decomposed separately using DWT. At each level of decomposition, powers of different frequency bands based on the detail coefficients were estimated using the following equation:

$$\text{Power} = \sum_{i=1}^{i=n}(c_1 + \cdots + c_n)^2 \quad (3)$$

Where, c_1 to c_n are the detail coefficients at a particular level. Power contrast was determined by comparing the power of the SEMG signal in the 45th minute (P_{fat}) with the power of the SEMG signal in the 1st minute (P_{nf}) for different frequency bands:

$$Contrast = absolute\left(\frac{P_{fat}-P_{nf}}{P_{nf}}\right) \times 100\% \quad (4)$$

Statistical analysis

The effect of fatigue induced by continuous repetitive exertions on the power in different frequency bands was analyzed using a mixed model analysis of variance (ANOVA). The fixed effect of time was set at four levels: exertions at the beginning and the end of session 1 (T=0 and T=20) and session 2 (T=25 and T=45). 'Participant' was treated as a random factor. The hypothesis was tested for the effect of time on the power of each band at 95% confidence level in SAS version 9.2.

RESULTS

The mean subjective discomfort in the right upper trapezius and left sternocleidomastoid muscles showed an increasing trend towards the end of sessions 1 and 2. A baseline discomfort of 1 (= nothing at all) was recorded at the beginning of the first session (T=0) for both muscles. After twenty minutes of loading and unloading tasks (T=20), for right upper trapezius muscle mean discomfort increased to 5 (= moderate discomfort). The corresponding discomfort for sternocleidomastoid muscle, increase to 3 (= very slight discomfort). At the end of forty minutes of monotonous cyclic loading and unloading tasks (T=45), a mean subjective discomfort increased to 7 (= some difficult discomfort) and 5 for the upper trapezius and sternocleidomastoid muscles, respectively (Table 2).

Table 2: Mean subjective discomfort at different time instances. Numbers in parenthesis represent one standard deviation

	T = 0	T = 20	T = 45
Right upper trapezius region	1 (0)	5 (1.2)	7 (0.6)
Left sternocleidomastoid region	1 (0)	3 (0.4)	5 (0.7)

For all the six wavelets tested in this study, mean power was relatively very low in the 375 -750 Hz and 6-12 Hz frequency bands. Therefore, these bands were not considered for the statistical analysis.

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The effect of time was statistically not significant for the power in the 46-93 Hz, 93-187 Hz, and 187-375 Hz frequency bands. For the lower frequency bands i.e. 23-46 Hz and 12-23 Hz, power estimated by Sym 5, Sym7, Bior1.3, and Bior3.1 wavelet functions was significantly ($P<0.05$) affected by the time for the right upper trapezius muscle (Table 3). The mean power at the end of session 1 (T=20) was higher than that at the beginning of session 1 (T=0). A slight decline in the power was observed following the rest period (T=25). At the end of session 2 (T=45), the power was higher than that at the beginning of session 1 (T=0) and 2 (T=25) (Figure 3(a)). For the sternocleidomastoid muscle, general trend of mean power with respect to time was similar to the upper trapezius muscle. However, effect of time on the power of the SEMG signal was statistically not significant for any of the wavelet functions (Figure 3(b)).

Table 3: P-values for the effect of time on the power of SEMG signal in various frequency bands for different wavelet functions. Statistically significant values are marked with asterisks (*).

	Upper trapezius muscle				
Wavelet function	187-375 Hz	93-187 Hz	46-93 Hz	23-46 Hz	12-23 Hz
Sym 5	0.875	0.711	0.229	0.023*	0.021*
Sym7	0.766	0.780	0.202	0.036*	0.003*
Dmey	0.979	0.951	0.367	0.171	0.213
Db2	0.920	0.844	0.6494	0.243	0.336
Bior1.3	0.543	0.380	0.128	0.020*	0.003*
Bior3.1	0.975	0.814	0.240	0.027*	0.020*
	Sternocleidomastoid muscle				
Sym 5	0.133	0.097	0.205	0.167	0.357
Sym7	0.267	0.073	0.230	0.152	0.273
Dmey	0.198	0.179	0.126	0.215	0.997
Db2	0.435	0.228	0.463	0.322	0.366
Bior1.3	0.139	0.116	0.178	0.219	0.285
Bior3.1	0.412	0.097	0.161	0.107	0.131

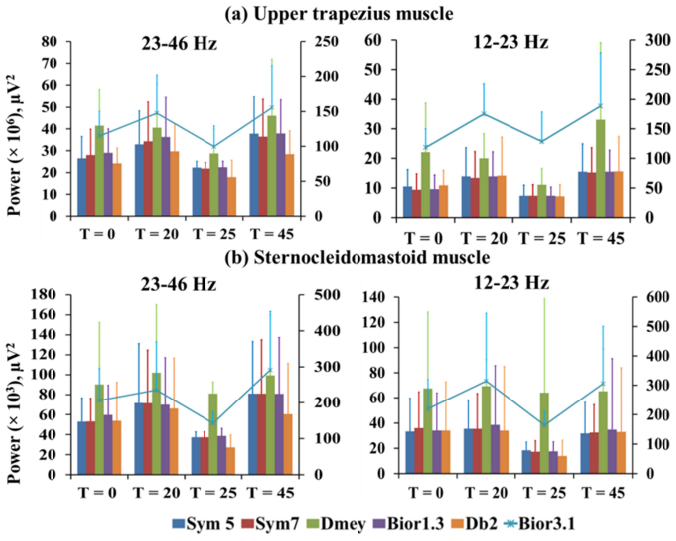

Figure 3: Mean power (μV^2) of lower frequency bands as a function of time for six wavelet functions. Power trend of Bior3.1 was plotted using a secondary axis.

A between wavelet comparisons showed that Bior3.1 wavelet estimated the highest power compared to the other five wavelets (Figure 3). The highest power contrast was also found for Bior3.1 wavelet in the 12-23Hz and 23-46Hz frequency bands for the upper trapezius and sternocleidomastoid muscles (Figure 4).

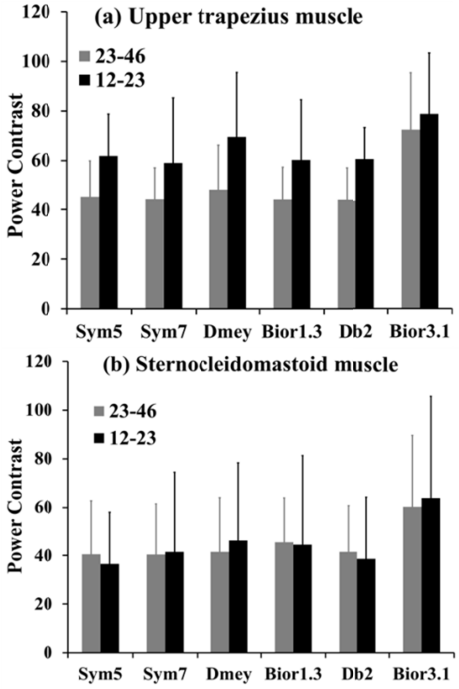

Figure 4: Power contrast estimated by different wavelet functions.

DISCUSSION & CONCLUSION

In this study, spectral changes in the SEMG of neck and shoulder muscles induced by sustained dynamic arm and neck exertion were studied using DWT analysis. With the onset of fatigue, a significant increase in the power of lower frequency bands (23-46Hz, and 12-23Hz) was observed for right trapezius muscle. For the sternocleidomastoid muscle the power increase at lower frequency bands was statistically not significant but the trend of power increase with respect to time was noteworthy. Higher sensitivity of power in the lower frequency bands with the development of muscle fatigue observed in this study is consistent with previous DWT based muscle fatigue assessment studies (Dolan et al., 1995; Kumar et al., 2003; Sparto, Parnianpour, Barria, & Jagadeesh, 1999).

Spectral changes estimated by DWT analysis were found to be dependent on the wavelet function used in the analysis. Shape matching of a wavelet function with the trains of motor unit action potential affects the detail coefficients estimated by DWT analysis. A high amplitudes of detail coefficients signify a good matching, whereas mismatch produces low amplitudes (Samar, Bopardikar, Rao, & Swartz, 1999). Although, most of the wavelet functions, tested in this study, reasonably demonstrated the expected power trend with fatigue development and recovery, some wavelets performed better

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than others. The highest power of the detail coefficient was observed for Bior 3.1. This wavelet also showed statistically consistent and meaningful trend not only in the12-23 Hz but also in the 23-43 Hz frequency bands. Furthermore the highest overall power contrast was also observed for this wavelet. Previously, Kumar et al., (2003) reported that the Sym4 and Sym5 wavelet functions estimated better power contrast between the fatigued and non-fatigued SEMG signal for the biceps-bracii muscle. For the low back muscle fatigue estimation, Sparto et al., (1999) used Daubechies 6 (db6) wavelet function. Overall the results of this study indicate that "Biorthogonal with 3.1 scales (Bio3.1)" wavelet function predict the fatigue induced spectral changes in the neck and shoulder SEMG signal with high accuracy among the six wavelets tested in this study.

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