Spectral Analysis of Root-Mean-Square Processed Surface Electromyography Data as a Measure of Repetitive Muscular Exertion

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Highly repetitive motion is associated with development of upper extremity musculoskeletal disorders (UEMSDs) among industrial workers, especially when encountered concurrently with forceful exertions. Current measures of "repetitiveness" provide information about the repetitiveness of joint motion, but fail to provide complete information about the *repetitiveness of muscular exertion*, a more biomechanically meaningful measure of repetition. The current study introduces a novel processing technique in which surface electromyography (sEMG) data is root-mean-square processed prior to computation of the frequency spectrum. The mean power frequency of the resulting power spectrum is the proposed metric for estimation of muscular exertion frequency. The metric was compared to joint movement and applied force frequencies during a series of isometric gripping trials and an industrial simulation. Results suggest that the proposed metric has potential to be a valuable metric to estimate exposure to repetitive muscular exertion.

INTRODUCTION

Across industries, work-related musculoskeletal disorders (MSDs) represent about 28% of all non-fatal occupational injuries and illnesses (Bureau of Labor Statistics., 2010). MSDs of the upper extremities (UEMSDs) comprise 24% of all reported MSDs, resulting in substantial adverse health effects and economic consequences (Bureau of Labor Statistics, 2010; Mayer, Gatchel, Polatin, & Evans, 1999). Occupational risk factors for UEMSD development include exposure to repetitive exertions, high hand force, and awkward postures (Chiang et al., 1993; Gerr, Letz, & Landrigan, 1991; Silverstein, Fine, & Armstrong, 1987; Stock, 1991). Imprecise and potentially biased exposure assessment methods commonly used in epidemiologic studies limit characterization of exposure-effect relationships between physical risk factors and UEMSDs. Many available methods for assessing exposure to repetitive activities fail to capture information about the frequency of muscular exertions, relying instead on worker self-report, observer judgment, or measurement of repetitive *joint motion* (as a surrogate for repetitive voluntary *muscular exertion*) with error-prone instrumentation.

Observational measures of exposure to repetition among assembly line workers have included the cycle time (Chiang et al., 1993; Malchaire et al., 1997; Silverstein et al., 1987) or ratings of motion speed by trained observers (Ebersole & Armstrong, 2006; Latko et al., 1997; Wurzelbacher et al., 2010). Because definitions of repetition vary among these methods, comparisons across observational studies are difficult (Ketola, Toivonen, & Viikari-Juntura, 2001; Viikari-Juntura et al., 1996). Frequency domain analysis of electrogoniometer data has been used to estimate the frequency of joint motion (Juul-Kristensen et al., 2002; Radwin & Lin, 1993; Spielholz, Silverstein, Morgan, Checkoway, & Kaufman, 2001). Electrogoniometers, however, are prone to error and may restrict natural motion (Buchholz & Wellman, 1997; Chaffin, Anderson, & Martin, 1999; Jonsson, 1982). The above methods capture muscular exertions that result in joint motion. However, muscular exertions that fail to produce joint motion may contribute to UEMSD risk.

Few methods for estimating the frequency of muscular exertion are available. The Strain Index, an observational method, requires observers to rate the duration of muscular exertions and judge whether the exertions are "forceful" (Moore & Garg, 1995). The criterion for defining an exertion as forceful is not standard, however.

Surface electromyography (sEMG) is a direct physiological measurement of muscle activation. Analysis of time-series sEMG data to estimate the frequency of muscular exertion has involved counting the number of times the signal amplitude exceeded a pre-determined threshold level (Cabeças, 2007; Malchaire et al., 1997). This technique, however, fails to provide information about variations in muscular exertions that do not cross the threshold level (i.e. that occur completely above or below the threshold level). The purpose of this study was to explore frequency domain analysis of root-mean-square (RMS) processed sEMG as a means to estimate the frequency of muscular exertion.

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MATERIALS AND METHODS

Study Population

A convenience sample (n=25) was recruited from the University of Iowa community. Participants (15 males, mean age = 27.8, SD=8.1) reported no history of physician diagnosed UEMSD or prior upper extremity surgery. Participants provided written informed consent, and were monetarily compensated for their time.

Surface Electromyography Procedures

Surface EMG instrumentation and procedures. Myoelectric activity of the extensor digitorum communis was obtained on the dominant side. Standard, preamplified electrodes (model DE2.3, Delsys Inc., Boston, MA) and established electrode placement protocols were used (Cram & Kasman, 1998; Zipp, 1982). The raw sEMG signals were 1) amplified (Bagnoli-16, Delsys Inc., Boston MA) 2) digitally sampled at 1000 Hz and 3) stored on a personal computer for later processing and analysis.

Surface EMG pre-analysis processing. Raw sEMG recordings were visually scanned for transient artifacts. Transients were replaced with the mean value of the full sEMG recording, and the mean voltage of the raw sEMG was subtracted to remove DC offset. When observed, 60 Hz noise contamination was removed with an 8^{th} order Butterworth notch filter (corner frequencies of 59.5 and 60.5 Hz). The raw (1000 Hz) sEMG recordings were then converted to instantaneous RMS amplitude using a 100-sample moving RMS window with a 90-sample overlap. The RMS-processed sEMG files thus had an effective sampling rate of 100 Hz.

Surface EMG normalization procedures. Participants performed maximal isometric hand grip exertions (*i.e.*, MVC) for normalization using a calibrated hand grip dynamometer (Commander GripTrack, JTech Medical, Salt Lake City, UT). Participants assumed a seated posture with the forearm supported and the elbow flexed to 90 degrees, and engaged the dynamometer in a power grip. MVC was defined as the maximum hand grip force recorded across three repetitions of the maximal hand grip procedure. The instantaneous RMS sEMG amplitude at the time of the MVC was used for normalization purposes.

The resting sEMG amplitude was also measured while participants sat in a relaxed posture for 60 seconds. The resting level was defined as the lowest mean RMS amplitude over a 5 second period and was quadratically subtracted from all subsequent RMS sEMG amplitude values (Thorn et al., 2007).

Electrogoniometer Procedures

Angular displacement of the dominant wrist in the flexion/extension motion plane was measured with a flexible, bi-axial electrogoniometer (SG65, Biometrics Ltd., Ladysmith, VA). The output cable was attached to a signal conditioning amplifier (model 2310, Vishay Measurements Group, Raleigh, NC) which 1) powered the electrogoniometer, 2) allowed for zeroing of the output voltage while participants assumed a neutral posture, and 3) provided real-time low-pass filtering of the output voltage signal (4^{th} order Butterworth, 10 Hz corner frequency) prior to digitization. The electrogoniometer signal was digitally sampled at 1000 Hz and smoothed using a 100-sample moving average window and a 90-sample overlap to maintain temporal synchronization with the sEMG data.

Reference Instruments

Data collection for the study occurred in two distinct phases: isometric gripping trials and an industrial simulation (procedures described in the following sections). In each phase, a reference instrument was used to provide a record of applied hand force. During the isometric gripping trials, participants exerted hand grip force using a similar hand grip dynamometer used for sEMG normalization. The dynamometer was modified for use with a signal conditioning amplifier (model 2310, Vishay Measurements Group, Raleigh, NC) and allowed direct sampling of its internal pressure transducer output voltage. In the industrial simulation, a force platform (FP4060, Bertec Corp., Columbus, OH) was used to provide a record of applied force. The voltage outputs from these devices were lowpass filtered (4^{th} order Butterworth, 10 Hz corner frequency) and sampled at 1000 Hz and transformed to forces using empirically derived (modified dynamometer) or manufacturer-supplied (force platform) calibration information. Force data were smoothed using a 100-sample moving average window and a 90-sample overlap to maintain temporal synchronization with the sEMG and electrogoniometer data.

Isometric Gripping Trials

Experimental methods. Participants were instructed to perform repetitive, isometric hand gripping exertions with their dominant hand using the modified hand grip dynamometer. The experimental conditions were characterized by intensity, duration, and frequency parameters. Intensity was defined as a target hand grip force applied to the dynamometer with two levels: 5%

MVC and 30% MVC. Duration was the proportion of an exertion period during which the target intensity was sustained (i.e. duty cycle). Duration had four levels: 75%, 50%, and 25% of full exertion cycle, and “burst” (<0.25 seconds in total duration). Frequency, in Hz, was the number of exertions per second. For each of the eight combinations of exertion intensity and duration, each participant was randomly assigned a unique frequency between 0.2 Hz (one exertion every 2 five seconds) and 1.0 Hz (one exertion every second).

A full factorial experimental protocol was used, meaning participants performed trials at all duration/intensity level combinations (8 trials per participant). To clarify the relationship among the parameters, if the assigned exertion frequency was 0.2 Hz, intensity was 30% MVC, and duration was 75%, the participant initiated a new exertion of 30% MVC once every five seconds and maintained that exertion for 3.75 seconds. Control of the task was achieved with a custom LabVIEW (version 2011, National Instruments, Austin, TX) program which provided a real-time visual display of information regarding the intensity, duration, and frequency parameters. Participants performed each trial for three minutes with a five minute rest between trials to avoid fatigue. The order of the eight trials was randomized.

Frequency domain analysis. All processed sEMG, electrogoniometer, and modified dynamometer recordings were transformed from the time domain into the frequency domain using the Fast Fourier Transform (FFT), resulting in power spectra for each data set and for each trial. From the power spectra, the mean power frequencies of the RMS-processed sEMG (MPF_{EMG}), the electrogoniometer (MPF_{ELG}), and the hand force (MPF_{HF}) were calculated. MPF_{EMG} is the proposed metric of muscular exertion frequency.

Statistical analysis. Pearson correlation analyses were used to estimate the strength of the linear relationships between MPF_{EMG} and MPF_{HF} ($r_{emg,hf}$) and between MPF_{ELG} and MPF_{HF} ($r_{elg,hf}$),. A repeated-measures ANOVA (alpha level of 0.05) was used to examine the effects of exertion intensity and duration on the difference between MPF_{HF} and MPF_{EMG}. Exertion intensity was a fixed effect with two levels (5% MVC and 30% MVC), duration was a fixed effect with four levels (75%, 50%, 25%, and burst), and participant was a random effect. Because each participant was randomly assigned a unique frequency, the participant effect could not be separated from frequency in the ANOVA model.

Industrial Simulation

Experimental methods. In the second phase of the study, participants were instructed to perform a repetitive, hand-intensive task requiring both muscular exertion and wrist joint motion. An experimental fixture adopted from Radwin & Lin (1993) was created (Figure 1). Twenty-four valves (3 rows of 8 valves) were mounted to an apparatus secured atop the force platform. An LED was attached to each valve, and each LED was wired to a unique port of a digital input/output device (USB 6501, National Instruments, Austin, TX). A custom LabVIEW program illuminated the lights in random order and at researcher-inputted frequencies. Prior to an experimental trial, each valve was set to a position requiring about one-third of a complete revolution (clockwise) to reach its angular displacement limit. During an experimental trial, participants assumed a seated posture and were instructed to turn the randomly illuminated valves to the angular displacement limit using the dominant (*i.e.*, instrumented) hand. Turning the valves required gripping, pushing, and rotating hand forces. A horizontal bar placed in front of the apparatus necessitated wrist flexion to reach the valves. Participants performed the industrial simulation task once at three standard frequencies (0.1 Hz, 0.166 Hz, and 0.5Hz) and once at a unique, randomly assigned frequency between 0.1 Hz and 0.5 Hz. The order of the four simulation trials was randomized.

Frequency domain and statistical analysis. All processed sEMG, electrogoniometer, and force platform recordings were transformed from the time domain into the frequency domain using the Fast Fourier Transform (FFT), resulting in power spectra for each data set and for each trial. Again, the MPF for each data set was computed (MPF_{EMG}, MPF_{ELG}, and MPF_{FP} respectively). The data from the unique frequency condition was used to calculate three Pearson correlation coefficients: $r_{emg,fp}$ (correlation between MPF_{EMG} and MPF_{FP}), $r_{emg,elg}$ (correlation between MPF_{EMG} and MPF_{ELG}), and $r_{elg,fp}$ (correlation between MPF_{ELG} and MPF_{HF}). Repeated-measures ANOVAs were used to estimate the fixed effect of frequency (with three levels: 0.5 Hz, 0.166 Hz, and 0.1 Hz) on 1) the difference between MPF_{FP} and MPF_{EMG} and 2) the difference between MPF_{FP} and MPF_{ELG}.

RESULTS

Isometric Gripping Trial Results

Figure 2 shows an example of the RMS-processed sEMG time series data, and Figure 3 shows the power spectrum of the same sEMG data. The data for this example were collected under the following experimental conditions: 50% duration, 30% MVC, and an assigned frequency of 0.47 Hz. Pearson correlation coefficients (*r)* assessing the strength of the linear relationships between MPF_{HF} and MPF_{EMG} and between MPF_{HF} and MPF_{ELG} for each exertion intensity/duration combination are presented in Table 1.

The effect of the interaction of exertion intensity and duration on the difference between MPF_{HF} and MPF_{EMG} was non-significant. Significant main effects of intensity and duration ($p<0.01$) on the difference between MPF_{HF} and MPF_{EMG} were observed. The differences were smaller at the high intensity (30% MVC) compared to the low intensity level (5% MVC). Similarly, smaller differences were observed during the shorter duration levels (burst, 25%, and 50%) compared to the longest duration level (75%).

Industrial Simulation Results

The observed Pearson correlation coefficients for the unique frequency condition of the industrial simulation were as follows: $r_{emg,fp} = 0.63$, $r_{elg,fp} = 0.71$, and $r_{emg,elg} = 0.59$. The difference between MPF_{FP} and MPF_{EMG} was significantly smaller for the medium and slow frequency conditions (0.1 Hz and 0.166 Hz) compared to the fastest frequency (0.5 Hz) (frequency main effect $p<0.01$). The difference between MPF_{FP} and MPF_{ELG} was also significantly smaller for the medium and slow frequency conditions compared to the fastest frequency (frequency main effect $p<0.01$).

DISCUSSION

The RMS-processing of the sEMG data altered the signal frequency content when compared to the power spectra of raw sEMG data (similar to full wave rectification followed by low-pass filtering). In the power spectra of RMS-processed sEMG, there is a concentration of signal power at frequencies generally below 10 Hz. Consequently, the power spectra of RMS-processed sEMG signals may provide information about the frequency (*i.e.*, repetitiveness) of muscular exertion. In this study, MPF_{EMG} was introduced as an index of muscular exertion frequency.

Results from the isometric gripping trials suggest that MPF_{EMG} had a stronger linear relationship with MPF_{HF} than MPF_{ELG} in all combinations of intensity and duration. This may indicate that MPF_{EMG} provides a better estimate of repetitiveness during isometric activities than MPF_{ELG}, as expected. The smallest differences between MPF_{EMG} and MPF_{HF} were observed for the higher intensity level and the shorter duration levels. The power spectra of the sEMG data during low intensity and long duration trials contained spectral content at higher frequency levels, resulting in higher than expected values of MPF_{EMG}.

Results from the industrial simulation trials suggest that there was a stronger linear relationship between MPF_{ELG} and MPF_{FP} than MPF_{EMG} and $MPF_{FP.}$ However, the difference between $r_{elg,fp}$ and $r_{emg,fp}$ was not meaningful and $r_{emg,elg}$ was moderate-to-strong, suggesting that MPF_{EMG} and MPF_{ELG} provided similar information about the frequency of muscular exertion. The ANOVA results from the industrial simulation data indicated that the frequency of the task had an effect on the agreement between the measure of repetition (MPF_{EMG} and MPF_{ELG}) and the external force measurement (MPF_{FP}).

The goal of this research was to develop methods to assess exposure to repetitive muscular exertion. The proposed metric (MPF_{EMG}) is not intended to measure task cycle time. Results of this study suggest that frequency analysis of RMS-processed sEMG can be used to estimate repetitive muscular exertion. Exploration of alternate filtering techniques and processing parameters may improve the performance of MPF_{EMG} as a metric of muscular exertion frequency.

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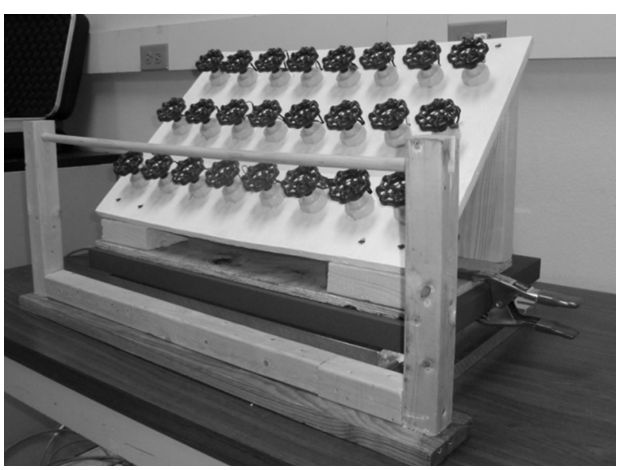

Figure 1. Industrial simulation apparatus

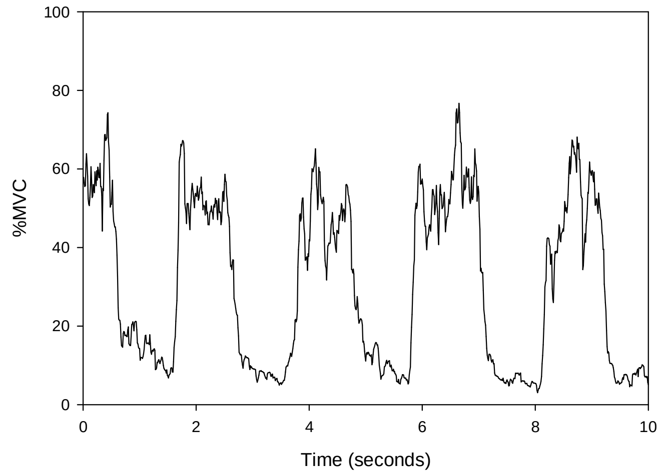

Figure 2. RMS- processed Time Series sEMG data

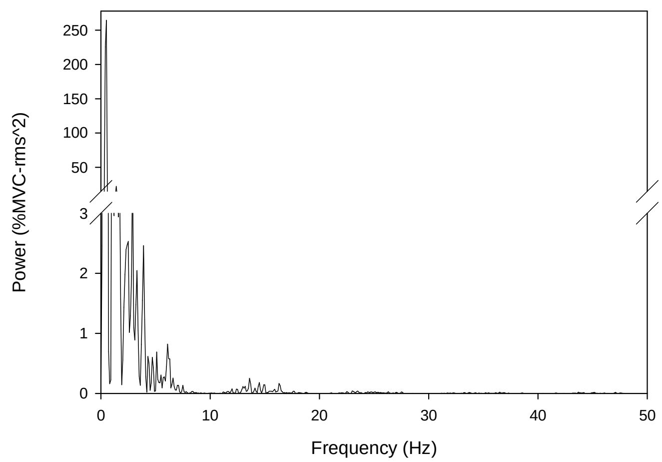

Figure 3. Power spectrum of RMS-processed sEMG data

Table 1. Pearson correlation coefficients for Phase 1

Intensity	Duration	$r_{emg,hf}$	$r_{elg,hf}$
5% MVC	Burst	0.09	0.06
	25%	0.68	-0.22
	50%	0.47	-0.17
	75%	-0.02	-0.02
30% MVC	Burst	0.93	0.30
	25%	0.92	0.11
	50%	0.72	-0.17
	75%	0.49	0.21