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EXPOSURE ASSESSMENT OF BIOMECHANICAL STRESS IN REPETITIVE MANUAL WORK USING SPECTRAL ANALYSIS

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Theory for a quantitative exposure assessment strategy is presented for measuring physical stress associated with manual tasks containing repetitive motion, postural stress, and forceful exertions. Physical stress is measured directly using electrogoniometers for articular motion, and sensors or electromyography are used for assessing forceful exertions. A method is described for reducing the large quantities of biomechanical data that can be recorded for repetitive manual work into quantifiable metrics based on recognized exposure factors, including repetitiveness, postural stress, forcefulness, and duration. A frequency domain approach is used for averaging elemental data from repetitive cycles. This paper shows how parameters for frequency-weighted filters may be developed from psychophysical data for equivalent discomfort levels. Low force repetitive wrist flexion was used as an example of the feasibility for implementing this approach. Applications of this theory include assessing exposure to physical stress in a manner analogous to the way sound level meters are used for measuring exposure to acoustic noise. A suitable data reduction method is necessary for conducting large scale detailed epidemiological investigations of cumulative trauma disorder risk factors. Development of frequency-weighted filters based on human response to stress at different frequencies may make it possible to establish quantitative exposure limits.

INTRODUCTION

Upper extremity cumulative trauma disorders (CTD) are often associated with repeated exertions and movements of the body, forceful exertions, extreme postures, and sustained exertions or postures. Nevertheless, adequate exposure assessment methods for the physical stress of repetitive manual work are not yet available. Detailed dose-response data has not been attainable due to the lack of practical measurement technologies and analytical methods necessary for measuring and quantifying these stresses in the workplace. Consequently quantitative exposure guidelines and standards for these physical stresses cannot be established or practically applied.

Technology is emerging that can provide researchers with direct quantitative measurements of biomechanical stress, including articular joint motion and forces exerted. Electrogoniometers and video motion analysis systems measure joint rotation angles and segment movements, and force sensors and electromyographic measure external forces acting against the hands and fingers. Although these instruments can continuously measure body motion and forces involved in manual tasks, they can produce abundant amounts of data quite rapidly. Data management is therefore a critical issue. Consequently efficient methods are needed for reducing these large quantities of data into a usable form. Suitable analytical methods are not currently available for reducing and quantifying physical stress exposure.

One of the major limitations of using biomechanical data analysis for physical stress exposure assessment is that data extraction, reduction, and synchronization with specific work activities are tedious and time consuming, requiring a large amount of work hours for conducting major studies. Analysis of direct posture and force measurement has been practical only for limited observation time and for small numbers of individual workers.

Spectral analysis was demonstrated as a useful method for characterizing repetitive wrist motion and postural stress using a simple peg transfer task (Radwin and Lin, 1993). Power spectra were computed by stratifying data segments into individual work elements, divided by element terminal points associated with the task. Peak spectral magnitudes and frequency components corresponded closely with joint angular displacement amplitudes and repetition rates. Spectrum DC component magnitudes were directly related to sustained wrist postures.

This paper describes a method for quantitative exposure assessment of physical stress associated with repetitive manual work. Biomechanical data is reduced using a frequency domain approach for averaging data from cyclical work elements. The approach permits development of frequency-weighted filters based on human response to stress at different frequencies. Theory for this method and the feasibility of this approach are explored.

METHODS

Terminology

The analytical method investigated is based, in part, on traditional industrial engineering elemental analysis. It extends time and motion study (Niebel, 1988) to include biomechanical data, in addition to elemental time. Using this approach, complex tasks are divided into work elements, each element consisting of a sequential set of fundamental movements and exertions such as reach, grasp, move, etc. Each element E_n is distinct, having well defined terminal points and work content. When a task is repetitive, a series of elements are performed in a repeating sequence C, called a *cycle* such that: $C = \{E_n\} = \{E_1, E_2, E_3, \ldots\}$.

A cycle is a set containing one or more contiguous elements. When cycles are performed repeatedly they comprise an *activity* or a task. Activity A contains a contiguous set of similar repeating cycles, C_m such that:

$$A = \{C_m\} = \{C_1, C_2, C_3, \ldots\} = \Big\{ \{E_1, E_2, E_3, \ldots\}, \{E_1, E_2, E_3, \ldots\}, \{E_1, E_2, E_3, \ldots\}, \ldots \Big\}.$$

Jobs often consist of several activities performed in the course of a work day. Job J therefore contains a set of activities A_l, such that: $J = \{A_l\} = \{A_1, A_2, A_3, \ldots\}$.

Data Recording

Continuous direct measurements can be made using electrogoniometers, electromyography or force sensors. Data for this investigation was recorded using a Penny and Giles Biometrics model M110 strain gage wrist goniometer fastened across the wrist on the dorsum of the hand and forearm using two-sided tape. Analog signals were digitized, coded, and recorded onto the audio tracks of VHS tape in synchronization with video images of the worker performing the operation (Radwin and Yen, 1993). Computer interactive video tape analysis was used for automating data reduction, data management and exposure analysis. Analog signals from up to 32 sensors attached to the upper extremities are digitized, coded, and recorded onto the audio track of VHS tape for a sample rate of 60 Hz in synchronization with video images of the worker performing the operation. Sample time may last several hours, if necessary.

Data Reduction

Multimedia computer technology is used for reducing the data using a computer-controlled VCR for extracting biomechanical data associated with repetitive tasks for specific work elements. This system enables an analyst to review the tape while observing the work at any speed and in any order (real-time, slow motion, fast motion, or frame-by-frame in either the forward or reverse direction). The analyst interactively identifies terminal points that divide repetitive tasks into repetitive elements for each work cycle based on the work content. The computer then automatically extracts biomechanical data segments corresponding to the specific elements for signal processing and analysis.

Elapsed times t_{mn} for element n of cycle m, are also extracted from the video tape using the number of frames contained between element terminal points (see Figure 1).

Cycle time T_{C_l} for activity l is the sum of the mean elemental times for all of the elements contained in a cycle, such that:

$$T_{C_l} = \sum_{n=1}^{N} T_{E_n}.$$

Sampled biomechanical data are divided into segments corresponding to individual elements. This is made possible by having the computer maintain a table of video tape time codes for elemental terminal points. A Hanning window is applied to the time series data in order to prevent leakage, or end-point effects. The windowed data is then packed into a vector N points in length and padded with zeros.

Exposure Analysis

Spectrum are used for quantifying repetitiveness, postural or force stress magnitude, and sustained postures or exertions. Biomechanical data for cyclical work can be averaged by element after being transformed into the frequency domain, having the advantage of being independent of phase, and resulting in a multidimensional matrix of physical stress time series for each articulation instrumented, for every work element. Elemental data segments, $s_{mn}(t)$ time series can be continuous joint angles (wrist flexion in the case of this investigation) or force records (see Figure 1).

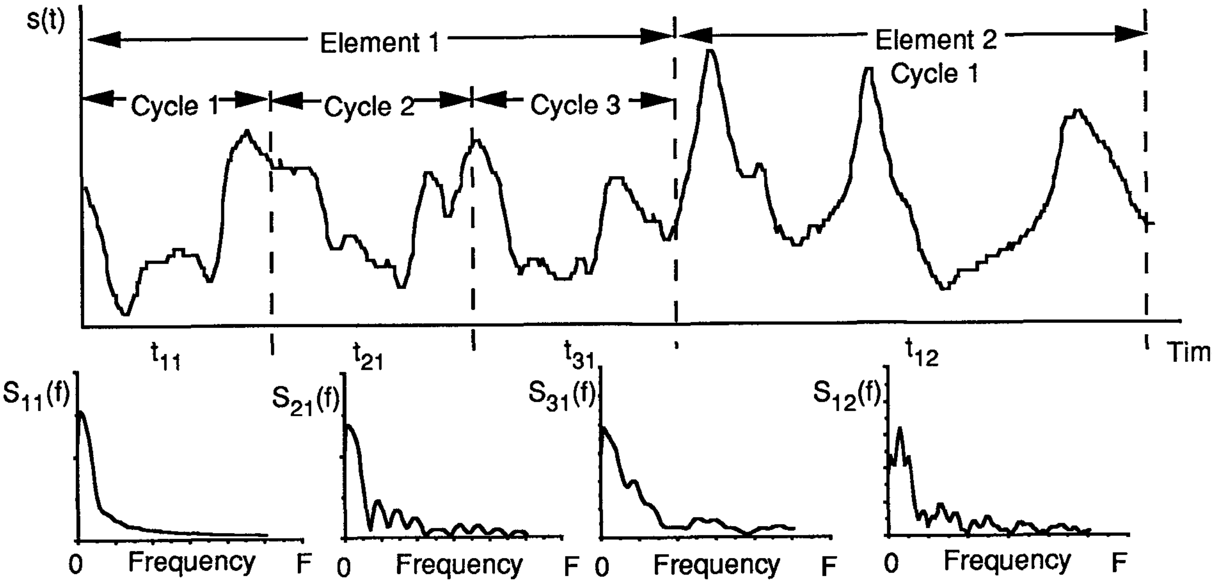

Figure 1: Spectra are computed for wrist flexion biomechanical time data extracted for every work element.

Extracted data for every element is transformed into the frequency domain using the fast Fourier transform (FFT) algorithm (Oppenheim, et al., 1988). The resulting complex transformation record is multiplied by its complex conjugate and divided by the square of the number of data points to compute the power spectral density magnitude. The FFT for biomechanical data segments, $s_{mn}(t)$ is computed using the relationship:

$$S_{mn}(f) = \sum_{t} s_{mn}(t) e^{-j2\pi ft}.$$

where $j = \sqrt{-1}$. Power spectra $S_{mn}{}^2$ are computed for each element n in cycle m

$$S_{mn}{}^2(f) = \frac{1}{N^2} |s_{mn}(f)|^2.$$

Power spectra for each element n then are averaged in the frequency domain for every cycle from $m= 1, \ldots, M$:

$$\bar{S}_n(f) = \frac{1}{M} \sum_{m=1}^{M} \sqrt{S_{mn}{}^2(f)}.$$

It is hypothesized that if frequency-weighted filters, *W(f)*, can be developed, corresponding to provisional human exposure response characteristics as a function of frequency, they can be applied to elemental spectra to produce a weighted sum of the spectrum frequency components such that:

$$\hat{S}_n(f) = \bar{S}_n(f) W(f)$$

Use of such filters, if they are feasible, have the benefit of enabling spectra to be reduced by integration into a single quantity for each element, without loosing sensitivity to properties of repetition, stress level, and sustained stress. Consequently, the total rms for the frequency-weighted spectrum can be computed as:

$$\bar{S}_n = \sum_{f} \hat{S}_n(f)$$

Exposure can be estimated from a time-weighted average for each activity l for a given stress on the body (ie. wrist flexion/extension) such that:

$$S_l = \frac{1}{T_{C_l}} \sum_{n} \bar{S}_n T_{E_n}$$

When L activities are performed for a total time T in a work day, the overall exposure for a given stress on the body (ie. wrist flexion/extension) can be expressed as:

$$S = \frac{1}{T} \sum_{l=1}^{L} S_l T_{C_l}$$

To test the feasibility of frequency-weighted filters, an experiment was conducted for studying the effects of repetition rate (frequency) and repetitive motion (wrist flexion angle) on subjective discomfort. A fixture was constructed for limiting wrist flexion limits, consisting of a bar attached by a perpendicular handle at one end and a pin joint at the other end. The approximate wrist joint center of rotation was aligned with the pin joint center. Subjects grasped a handle using the dominant hand as the wrist was repetitively flexed and extended at the wrist. Two mechanical stops were adjustable so wrist flexion can be limited between 0° and ±90°. The fixture was located on an adjustable height table. Subjects sat in an upright position with the forearm rotated in the neutral position with the elbow about waist height. The forearm and upper arm were positioned at a right angle. A bearing was installed in the pin joint and the handle and bar were made of light Plexiglas, so the load against the hand and wrist were negligible. Subjects repetitively flexed the wrist from the neutral position to the preset flexion limit. An electronic timer produced a tone indicating the pace.

The full-factorial experiment consisted of five paces and two wrist flexion angles. The timer produced a brief tone indicating to the subject to perform a wrist flexion every 1 s, 2.5 s, 5 s, 10 s, and 20 s. Wrist flexion was limited to 35° and 65°. The experiment was a repeated measures experiment where every subject received all treatments, and subjects was treated as a random effects blocking variable. Experimental conditions were presented in a random order and every subject performed all combinations of pace and wrist angle. Each experimental condition was performed for one hour. No two conditions were presented to a subject on the same day, and at least one day elapsed between experimental conditions. Subjects were required to be symptom-free at the beginning of every experimental session, otherwise the experiment was postponed until the following day. Five subjects were randomly recruited and paid on an hourly basis. All subjects were right handed females, ranging from 21 yr to 26 yr.

Discomfort was measured using the cross-modality matching method. Subjects marked localized discomfort on a 10 cm linear scale, anchored on the left as "no discomfort," and on the right as "very high discomfort." Localized forearm discomfort was assessed every fifteen minutes during a one minute break in the hour long experimental session. Symptoms of discomfort included aching, fatigue, soreness, warmth, cramping, pulling, numbness, tenderness, pressing, or pain. The length of the line was measured on a scale from 0 to 10 cm. Analysis of variance of log transformed discomfort data was used for determining statistically significant effects.

RESULTS

Mean discomfort ratings averaged over five subjects for all experimental conditions of wrist flexion angle (degrees) and pace (s/ movement) are shown in Figure 2. Wrist flexion angle ($F(1,4) = 40.5$, $p < .01$) and pace ($F(4,16) = 57.1$, $p < .001$) were significant main effects. No significant interaction between wrist flexion angle and pace was observed ($F(4,16) = 0.9$, $p > .1$).

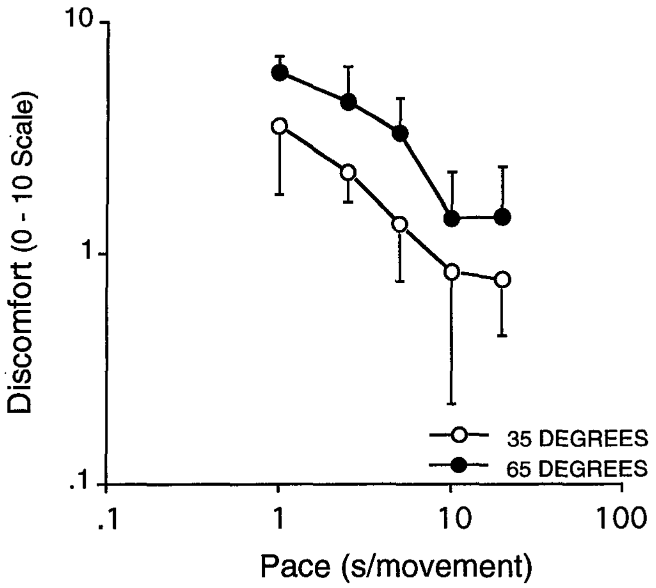

Figure 2: Average wrist flexion discomfort response and one standard deviation (5 subjects)

Pace was converted into frequency (Hz) by taking its inverse. A linear polynomial regression model for log transformed discomfort, fitted against wrist flexion angle limit and frequency (Hz) was produced, resulting in:

$$D = 10^{(0.17 + 0.45F + 0.01A)} - 1$$

($r^2 = 0.86$, $F(2,7) = 20.6$, $p < .001$), where D is discomfort (scale of 0 to 10), F is frequency (Hz), and A is the wrist flexion angle limit (degrees). Equal discomfort strata for wrist flexion were determined by solving the regression equation for flexion range at given frequencies for different discomfort levels . These strata are plotted against frequency (Hz) and wrist flexion range in Figure 3. The curves in Figure 3 indicate, for instance, that level 2 discomfort occurs for repetitive wrist flexion at a frequency of 0.2 Hz and wrist flexion limits of 62°, and that the equivalent discomfort level occurs at a frequency of 0.8 Hz and wrist flexion limits of 16°.

Another polynomial regression model was produced based on the log of F and the log of A, such that:

$$D = 10^{(-0.43+0.37\log F+0.70\log A)} - 1$$

($r^2 = 0.95$, $F(2,7) = 61.1$, $p < .001$), where D is discomfort (scale of 0 to 10), F is frequency (Hz), and A is the wrist flexion angle limit (degrees). This equation was used for specifying attenuation levels needed for high pass filters that weigh repetitive wrist flexion in proportion to the discomfort function. The slope of these filters were derived in the same manner as the linear equal discomfort strata. This resulted in a slope of 10 dB/ decade. The high-pass filter cutoff frequencies were set to the x-intercept of the linear equal discomfort lines (see Figure 3). High-pass filters derived from these equal discomfort strata are shown in Figure 4 for discomfort levels between two (little discomfort) and four (moderate discomfort).

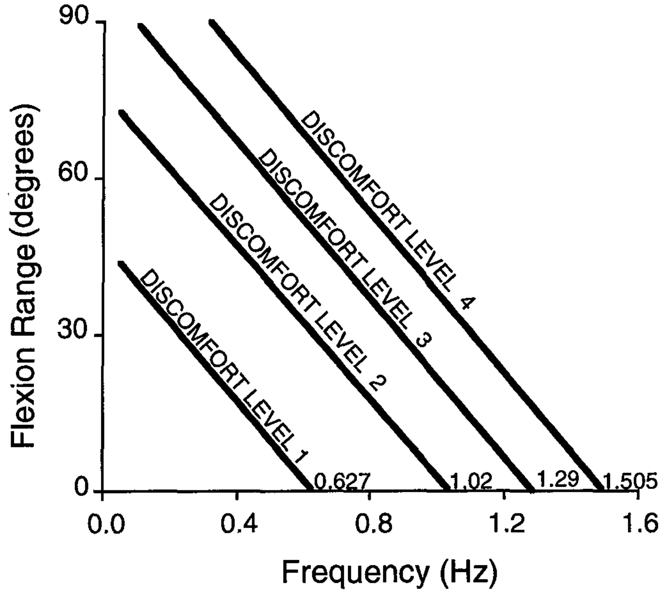

Figure 3: Equal discomfort strata based on wrist flexion discomfort

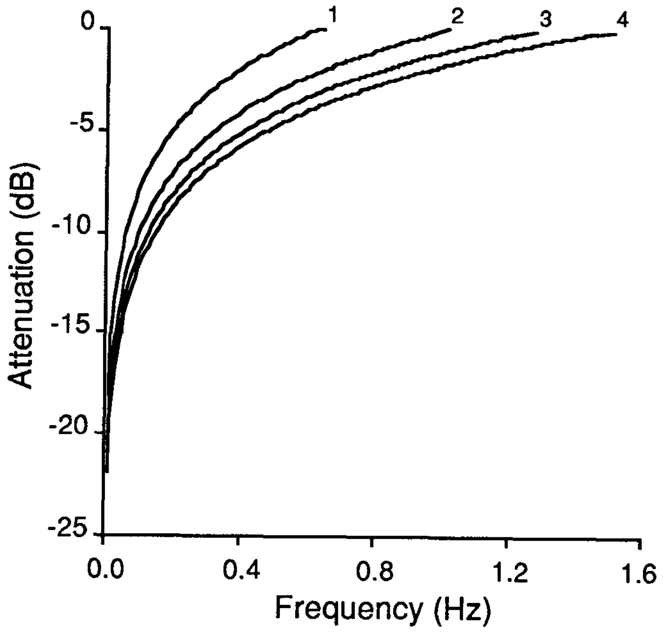

Figure 4: High-pass filters for frequency-weighted discomfort at discomfort levels 1 through 4.

DISCUSSION

The effect of frequency-weighted filtering was verified using sine waves in Figure 5. A sinusoid at a frequency of 0.2 Hz and a 61° peak (rms = 46°) had a similar frequency-weighted magnitude as another sinusoid at a frequency of 0.4 Hz and a 46° peak (rms = 35°). The rms was $\bar{S}_n = 20°$ for the 0.2 Hz sinusoid and $\bar{S}_n = 22°$ for the 0.4 Hz sinusoid after filtering. Therefore filtering normalized these two equivalent discomfort conditions. A sinusoid with a frequency of 0.2 Hz and a 46° peak (rms = 35°) had a 15° peak after filtering.

A simple task consisting of transferring pegs from one peg board to another peg board was performed for two paces (2 s/peg and 4 s/peg). An electronic timer produced a periodic tone for pacing the task. The unfiltered rms was 26° for the 2 s/ cycle task and 28° for the 4 s/ cycle task. The frequency-weighted rms was 18° for the 2s/ cycle task while it was 13° for the 4s/ cycle task indicating it was less stressful because it was less repetitive.

This investigation shows that frequency-weighted filters corresponding to discomfort responses associated with exertions and movements at specific frequencies can be developed. A frequency-weighted filter function could also be based on the inverse frequency characteristics of provisional exposure limits. For example, highly frequent repetitive movements are associated with a greater risk of incurring an injury, than for less frequent repetitive motions (Silverstein, et al., 1986). Hence, the frequency weighted filter function should be a high-pass filter, counting high frequency motions more heavily than low frequency motions, since high frequency motions are considered more hazardous. Frequency-weighted filters associated with specific movements at different frequencies and magnitudes should be developed corresponding to musculoskeletal disorder prevalence.

Marras and Schoenmarklin (1993) measured wrist flexion in terms of angular motion, velocity, and acceleration using an electrogoniometer for industrial subjects working in low and high risk jobs. Statistical analyses of these measures revealed that velocity and acceleration data of wrist motion discriminated significant differences between these two groups. Velocity and acceleration are first and second derivatives of angular motion. Differentiation is equivalent to a high-pass filter having a slope of 20 dB/ decade. The high-pass filters derived in this study provide frequency-weighted data that was proportional to differentiated data, only the slope was 10 dB/ decade. Consequently frequency-weighted produces data in agreement with the findings in Marras and Schoenmarklin's study. Furthermore, frequency-weighted wrist flexion data may indicate exposure magnitude on a scale proportional to relative discomfort.

Although this study was very limited, it demonstrates the feasibility of this approach. The actual parameters for this frequency-weighted function may be depended on (1) epidemiological data, (2) biomechanical data, or (3) phychophysical data. At present, none of these relationships are precisely known and should be the subject of future research.

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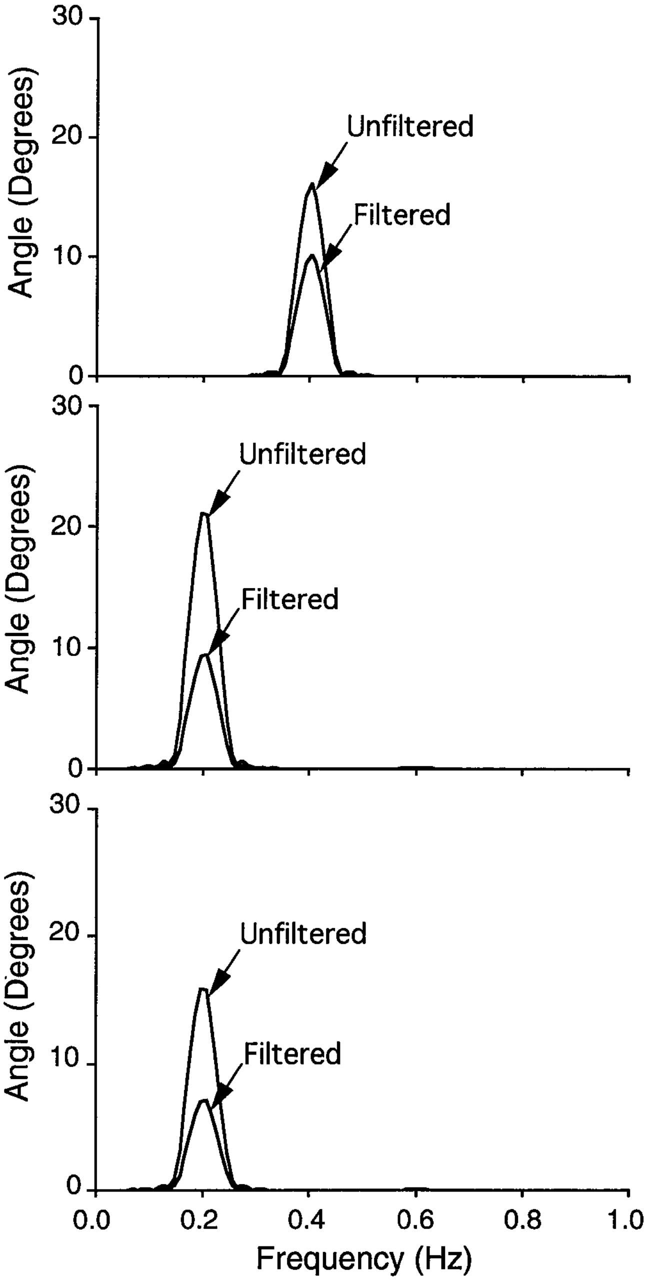

Figure 5: Spectra for sinusoidal test data illustrating effects of filtering for frequencies of 0.2 Hz and 0.4 Hz.