Rapid Communication

Exposure assessment of biomechanical stress in repetitive manual work using frequency-weighted filters

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A quantitative exposure assessment strategy for physical stress associated with repetitive manual tasks is proposed using continuous biomechanical data measured directly from electrogoniometers or force sensors. This paper describes an efficient method for reducing large quantities of biomechanical data into a quantifiable metric that accounts for recognized musculoskeletal exposure factors, including repetitiveness, postural or forceful exertion stress, and duration. A frequency domain approach is used for averaging elemental data recorded for repetitive cycles. Parameters for frequency-weighted filters are developed using psychophysical data for equivalent discomfort levels resulting from repetitive movements of different amplitudes and frequencies. These filters enable continuous biomechanical data to be filtered and integrated, resulting in a single quantity corresponding to psychophysical response characteristics for repetitive motion stress. It is anticipated that a similar approach may be used for epidemiological response characteristics. Applications of this theory may make it possible for assessing exposure to physical stress in a manner analogous to the way in which sound level meters are used for measuring exposure to acoustic noise. Repetitive wrist flexion and localized discomfort was used for demonstrating the feasibility of this approach. Suitable data reduction techniques are necessary for evaluating work methods, job designs, and for conducting large scale detailed epidemiological investigations of cumulative trauma disorder risk factors. Frequency-weighted filters based on human response to physical stress at different frequencies can greatly simplify exposure analysis and ultimately may make it possible for quantitative exposure limits to be established.

1. Introduction

Electrogoniometers and other motion analysis systems are capable of measuring joint rotation angles and body segment movements, and can provide ergonomics practitioners and researchers with direct quantitative measurements of biomechanical stress in repetitive manual work. Although these instruments can continuously measure body motions involved in manual tasks, they can produce abundant amounts of data quite rapidly. Suitable analytical methods are not currently available for efficiently reducing and quantifying physical stress exposure.

One of the major limitations of using biomechanical data analysis for physical stress exposure assessment is the large overhead associated with managing large quantities of data for complex tasks performed during manual work. 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 continuous posture and force measurements has therefore been practical only for limited observation time and for relatively small numbers of workers (Moore *et al.* 1991, Marras and Schoenmarklin 1993). Video based data acquisition methods are now available for simultaneously recording biomechanical data in synchronization with video images,

making it possible to record large quantities of data and interactively extracting data for analysis corresponding to specific videotaped events (Radwin and Yen 1993).

Spectral analysis was demonstrated as a useful analytical method for characterizing repetitive wrist motion and postural stress using simple peg transfer tasks (Radwin and Lin 1993). Power spectra were computed by stratifying data segments into individual work elements, divided by elemental 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 posture. The method was also capable of distinguishing different levels of postural and repetitive motion stress between different task factors.

A method is presented here for assessing exposure to physical stress associated with repetitive manual work. The method described can reduce biomechanical data into a metric corresponding to recognized exposure factors, including repetitive motion, postural stress and duration. The approach utilizes traditional industrial engineering elemental analysis. The frequency domain is used for averaging data from cyclical work elements. This study investigates whether frequency-weighted filters can be established based on short-term psychophysical responses (discomfort) to repetitive motion stress at different movement amplitudes and frequencies. Theory for this analytical method and the feasibility of implementing this approach are explored.

2. Methods

2.1 *Terminology*

The analytical method investigated in this paper extends traditional industrial engineering time and motion study elemental analysis (Niebel 1988) to include biomechanical data, in addition to measuring temporal aspects of manual work. A job may consist of several tasks or activities performed during the course of a work day. Using this approach, job J is divided into a set of L specific work activities, A_l such that:

$$J = \{A_1 A_2, A_3, \ldots A_L\}.$$

Each activity, A_l consists of one or more repeating cycles, C_{lm} that are performed M times such that:

$$A_l = \{C_{l1}, C_{l2}, C_{l3}, \ldots, C_{lM}\}.$$

A cycle, C_{lm} contains N contiguous work elements, E_{lmn} that describe the activity such that:

$$C_{lm} = \{E_{lm1}, E_{lm2}, E_{lm3}, \ldots, E_{lmN}\}.$$

An element is traditionally broken into a sequential set of P fundamental operations consisting of basic motions and exertions, O_{lmnp} such as reach, grasp, move, etc., where:

$$E_{lmn} = \{O_{lmn1}, O_{lmn2}, O_{lmn3}, \ldots, O_{lmnP}\}.$$

This sequence of operations are repeated every time element E_{lmn} occurs. Each element is distinct, having well defined terminal points and work content. These relationships are summarized in figure 1.

Traditional time and motion study quantifies each element by its mean elapsed time. If the elapsed time for element E_{mn} is t_{mn}, the mean elapsed time T_{E_n} for M cycles is
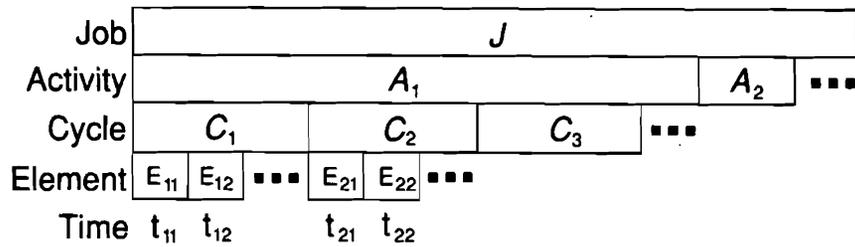
Figure 1.   Job (J) is divided into a set of work activities (A) that consist of repeating cycles C containing elements (E). Traditional time and motion study characterizes each element by its elapsed time (t).

computed as:

$$T_{E_n} = \frac{1}{M} \sum_{m=1}^{M} t_{mn}.$$

The mean cycle time, T_{C_l} for a cycle of activity A_l is usually estimated from the sum of mean elemental times for all N elements contained in a cycle, such that:

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

Time study data is useful for evaluating physical stress exposure. The duration for a specific work element can be measured directly from a time study as the mean elapsed time, T_{E_n}. The frequency, F_{E_n} that work element E_n repeats in activity A_l (expressed in terms of the number of repetitions per unit time) is sometimes estimated from the reciprocal of the cycle time, T_{C_l}, such that:

$$F_{E_n} = \frac{1}{T_{C_l}}.$$

Cycle time has been used previously as a metric for repetitiveness (Armstrong *et al.* 1982, Silverstein *et al.* 1986). One difficulty in using that method is that often fundamental operations are repeated within an element. Therefore in order to accurately characterize repetitiveness, the cycle must be divided further into smaller elements, thereby reducing the number of fundamental operations P contained in an element, making T_{E_n} small. As T_{E_n} decreases, the analysis that customarily involves frame-by-frame examination of a videotape, becomes very tedious. Furthermore, this type of analysis only measures the repetition and duration of the task but does not quantify the magnitude of the physical aspects of the movements and exertions. Biomechanical data may be introduced by incorporating continuous direct measurements into the analysis.

2.2. *Data recording and reduction*

Although the method described in this paper is applicable to many different continuous measurement technologies, biomechanical data for this investigation was recorded using a Penny and Giles Biometrics model M110 strain gauge wrist goniometer. The device was fastened across the wrist on the dorsum of the hand and the forearm using double-sided tape.

A data recording system that records analogue data in synchronization with video images of the worker performing the operation can be used for extracting biomechanical measurements synchronized with specific events (Radwin and Yen 1993). Analogue signals from as many as 32 sensors attached to the upper extremities can be sampled

at a rate of 60 points/s, digitized, coded , and recorded on to the audio track of VHS tape together with video image. Data sampling of up to several hours is possible using this system.

Interactive multimedia computer technology can be used for reducing the data and extracting biomechanical data associated with repetitive tasks for specific work elements using a computer-controlled VCR. This system enables an analyst to review the tape while observing the work at any speed and in any sequence (real-time, slow motion, fast motion, or frame-by-frame in either the forward or reverse direction). The analyst reviews the videotape and interactively identified element terminal points. Terminal points are characteristic events or movements that define the start and end of an element, such as touching or releasing a specific object. The computer maintains a look-up table of videotape time codes containing every elemental terminal point.

The computer can then automatically extract the kinematic data segments corresponding to the specific elements for signal processing and analysis. Since the video tape has a resolution of 60 Hz, each video frame represents $1/60 \, \text{Hz} = 16 \, \text{ms}$. Sampled biomechanical data can then be divided into time series segments corresponding to individual elements.

2.3. *Exposure analysis*

The upper extremity kinematic data recorded for each element may be included in the elemental analysis using the following approach. Rather than describing an element using fundamental motion descriptors, O_{mnp} as traditional time-and-motion study does, element E_{mn} is considered as an array of angular movements, $a_{mni}(t_j)$ for each articulation i such that:

$$E_{mn} = \{ a_{mn1}(t_j), a_{mn2}(t_j), a_{mni}(t_j), \ldots, a_{mn14}(t_j) \}.$$

where:

$$i = \begin{cases} 1, & \text{left wrist flexion/extension} \\ 2, & \text{right wrist flexion/extension} \\ 3, & \text{left wrist ulnar/radial deviation} \\ 4, & \text{right wrist ulnar/radial deviation} \\ 5, & \text{left forearm pronation/supination} \\ 6, & \text{right forearm pronation/supination} \\ 7, & \text{left elbow flexion/extension} \\ 8, & \text{right elbow flexion/extension} \\ 9, & \text{left shoulder flexion/extension} \\ 10, & \text{right shoulder flexion/extension} \\ 11, & \text{left shoulder adduction/abduction} \\ 12, & \text{right shoulder adduction/abduction} \\ 13, & \text{left shoulder lateral/medial rotation} \\ 14, & \text{right shoulder lateral/medial rotation} \end{cases}$$

for the upper extremities, and t_j are discrete time samples. The corresponding data segments are extracted using elemental terminal points saved in the computer look-up table as the boundaries for the data time series. For most industrial activities, this matrix can contain many millions of data points. The following describes a method how this data may be reduced.

Spectra are used for quantifying repetitiveness, postural stress magnitude, and sustained posture (Radwin and Lin 1993). The frequency domain enable averaging of
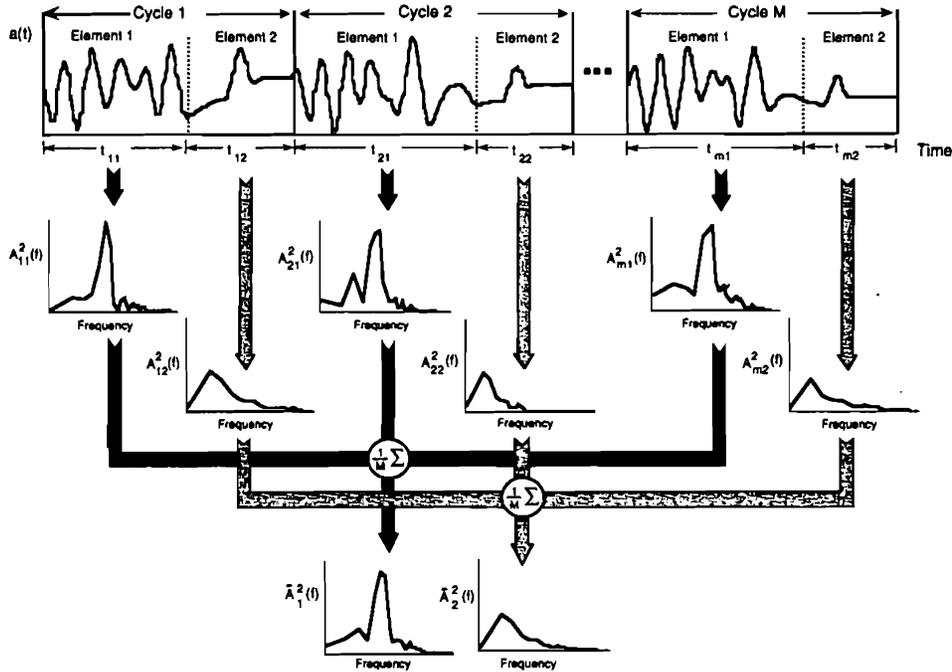
Figure 2. Spectra are computed for biomechanical time data $a_{mni}(t)$ extracted for every work element.

elemental biomechanical data, where averaging in the time domain may not be feasible. Time averaging is not usually practical because of variations in synchronization of biomechanical data with respect to time from element to element. The resulting analysis provides a matrix of frequency transformed biomechanical time series data for every work element, E_{mn} and for each articulation i. For the current investigation, angular movement time series segments, $a_{mni}(t)$ were simply continuous wrist flexion angles (see figure 2).

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 K points in length and padded with zeros. Extracted time series data for every element is transformed into the frequency domain using the fast Fourier transform (FFT) algorithm (Oppenheim *et al.* 1983). The frequency domain angular movement, $A_{mni}(f_k)$ for time domain biomechanical data segment, $a_{mni}(t_j)$ is expressed as a function of discrete frequency f_k. 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:

$$A^2_{mni}(f_k) = \frac{1}{K^2} \, |A_{mni}(f_k)|^2$$

Power spectra for each articulation i of element n are then averaged over M cycles and integrated in the frequency domain. The total power, $\bar{A}^2_{mni}$ for articulation i of element n and cycle m is summed over all frequencies f_k:

$$\bar{A}^2_{mni} = \sum_{k=1}^{K} A^2_{mni}(f_k).$$

By Parseval's theorem for periodic signals, the root mean square (RMS) of $a_{mni}(t_j)$ is simply the square root of $\bar{A}^2_{mni}$:

$$\text{RMS} = \sqrt{\frac{1}{J} \sum_{j=1}^{J} a^2_{mni}(t_j)} = \sqrt{\sum_{k=1}^{K} A^2_{mni}(f_k)} = \sqrt{\bar{A}^2_{mni}} = \bar{A}_{mni}$$

Therefore the average RMS, $\bar{A}_{ni}$ for articulation i of element n is obtained by averaging $\bar{A}^2_{mni}$ over M cycles and taking the square root:

$$\bar{A}_{ni} = \sqrt{\frac{1}{M} \sum_{m=1}^{M} \bar{A}^2_{mni}}$$

resulting in a single quantity that represents motion for each articulation and element.

Although this approach permits averaging elemential biomechanical data and reducing the movement data into a single RMS quantity, an undesirable consequence is that frequency information is lost. It is therefore hypothesized that if an appropriately scaled filter network can be derived so its frequency characteristics represent the characteristics of human response to physical stress, such as discomfort or occurrence of injury, the filtered biomechanical data would be proportional to those frequency characteristics. This concept is illustrated using the diagram in figure 3 where sine waves all having the same RMS input amplitude have high-pass filtered RMS output amplitudes that increase for increasing frequencies. Furthermore, if the high-pass filter cut-off frequency and slope were scaled so equivalent outputs were obtained for inputs of different combinations of frequency and amplitude that resulted in equivalent physical stress responses, then the output signal RMS would correspond to these equivalent physical stress levels. This concept is illustrated in figure 4 where different sine waves having decreasing RMS input amplitudes and increasing frequencies all have the same high-pass filtered RMS output amplitudes.

If such frequency-weighted filters, $W(f_k)$, can be developed corresponding to physical stress frequency responses, they can be applied to elemental spectra to produce a weighted sum of the spectrum frequency components $\hat{A}^2_{mni}$:

$$\hat{A}^2_{mni} = \sum_{k=1}^{K} A^2_{mni}(f_k) \cdot W(f_k)$$

which can be substituted for $\bar{A}^2_{mni}$ and used for computing the RMS. Use of such filters have the benefit of enabling spectra to be reduced through the process of integration into a single quantity for each element without losing properties of repetition and stress level. Hence, movement data can be averaged and integrated. and frequency characteristics corresponding to physical stress levels are retained. These filters would greatly simplify the analysis process, making it possible to assess physical stress using a process similar to the way noise measurements are made using a sound level meter. The resulting instrument is conceptualized in the block diagram shown in figure 5.

After the integrated filtered metric is determined, exposure may be assessed by using time-weighted averages of the filtered RMS, $\hat{A}_{ni}$ for each activity l and each articulation i by averaging over the mean cycle time, such that:

$$A_{li} = \frac{1}{T_{C_l}} \sum_{n=1}^{N} \hat{A}_{ni} T_{E_n}.$$

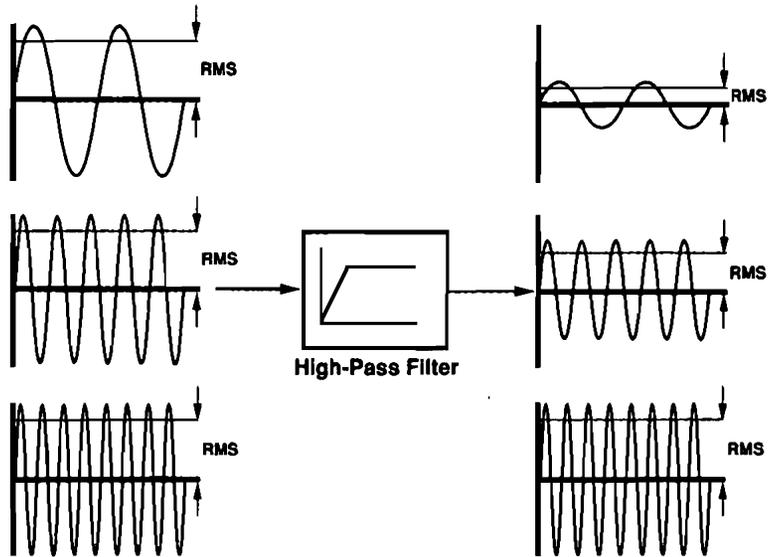Where L activities are performed in a work day of T duration, the overall exposure for
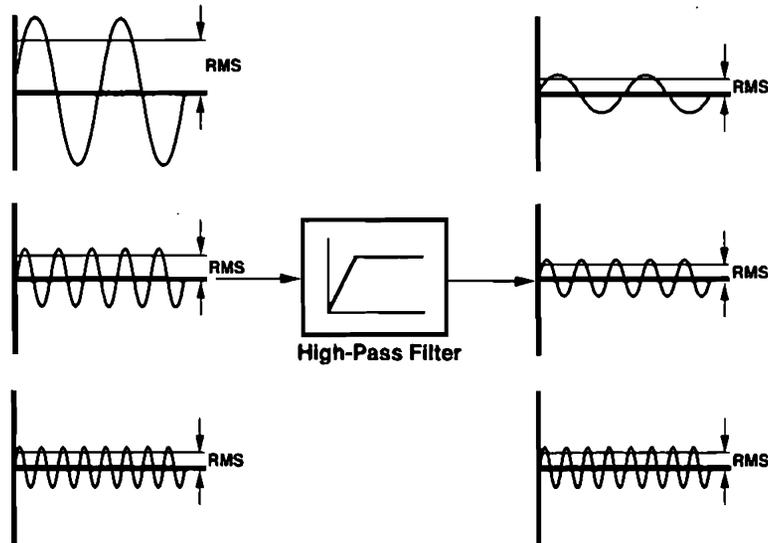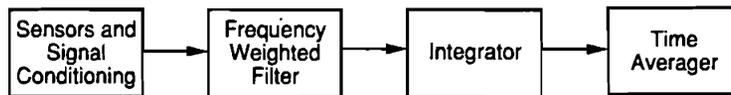
a body part *i* may be expressed as:

$$A_i = \frac{1}{T} \sum_{l=1}^{L} A_{li} T_{C_l}$$

This would result in a single metric that accounts for recognized musculoskeletal exposure factors, including repetitiveness, postural stress and duration.

2.4. *Experimental procedures*

To test the feasibility of deriving 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 and extension range, consisting of a Plexiglas bar having a perpendicular handle at one end and a pin joint at the other end. The approximate wrist joint centre of rotation was aligned with the pin joint. Subjects grasped the handle using the dominant hand, while the wrist was repetitively flexed and extended. Two mechanical stops were installed so that wrist flexion was limited between 0° and ± 90°, where 0° represented a neutral wrist angle, positive angles were flexion and negative angles were extension. A ball bearing was installed in the pin joint so that the load against the hand and wrist were negligible. The fixture was located on a table that was adjustable in height. Subjects sat in an upright position with the forearm pronated and the elbow joint maintained in a right angle. Subjects repetitively flexed the wrist from the neutral flexion 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. To indicate time to flex the wrist the timer produced a brief tone every 1 s (1 Hz), 2·5 s (0·4 Hz), 5 s (0·2 Hz), 10 s (0·1 Hz) and 20 s (0·05 Hz). Wrist flexion angle was limited to 35° and 65°. The experiment was a repeated measures experiment where every subject received all treatments, and subject was 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 continuously 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 age 21 to 26 years.

Discomfort was measured using the cross-modality matching method. Subjects marked localized discomfort on a visual analogue 10 cm linear scale, anchored on the left as 'no discomfort', and the right as 'very high discomfort'. The length of the line was measured on a scale from 0 to 10. Localized forearm discomfort was assessed every fifteen minutes during a one-minute break in the hour-long session. Symptoms of localized discomfort were described as aching, fatigue, soreness, warmth, cramping, pulling, numbness, tenderness, pressing or pain. Analysis of variance of log-transformed discomfort levels was used for determining statistically significant effects. Frequency-weighted discomfort filters were derived using equivalent discomfort levels for wrist flexion angle and frequency. This procedure is detailed in section 3.

A validation experiment was subsequently performed for testing the feasibility of using the derived frequency-weighted discomfort filters for a simple one-hole peg

transfer task. Seated subjects repeatedly transferred 7·5 cm long and 1 cm diameter pegs from a container on a table, over a horizontal bar directly in front of them, and inserted the pegs into a hole in a tilted peg board. The peg board had a single hole that was located at its centre. The purpose of the bar was to control wrist flexion angle when inserting pegs into the hole. After the pegs were inserted through the peg hole, they dropped down a chute that led them back into the container, so there was always an unlimited supply of pegs. The apparatus was set on a table that was adjustable in height so that the container was located at seated elbow height. Subjects sat in an upright position with the dominant shoulder aligned with the container and the peg hole. Since the eight gram peg weight was negligible, this was considered to be a low force task.

The validation experiment was 2 × 2 full factorial repeated measures design, where subjective discomfort was the dependent variable, and pace and wrist flexion angle were independent variables. Pace was controlled using a periodic tone burst sounding every 2 s (0·5 Hz) or every 5 s (0·2 Hz). The horizontal bar height was adjusted so that subjects had to assume either a 20° or 45° wrist flexion angle when inserting pegs into the hole. The container was located so that a neutral wrist posture was assumed when reaching and grasping the pegs. All experimental conditions were presented in counterbalanced order among subjects. The peg transfer task was performed for an hour and no two experimental conditions were presented to a subject on the same day. A two-minute warm-up period was provided at the start of each session. Four subjects were recruited and paid on an hourly basis. All subjects were right-handed, including three females and one male, ranging from age 21 to 31 years.

Discomfort was assessed every fifteen minutes during a one-minute break using the same rating scale as the previous experiment. The frequency-weighted discomfort filters derived in the previous experiment were implemented as described in the previous section. Wrist angular movements made while performing the one-hole peg task were recorded using the electrogoniometer and video-based data recording system. Biomechanical data was extracted for the last 15 min for each subject. The unfiltered and filtered average RMS amplitudes were estimated from that data sample. Discomfort ratings at the conclusion of each session were used in the analysis.

3. Results

3.1. Derivation of filter coefficients

Mean discomfort ratings averaged over five subjects for all ten experimental conditions of wrist flexion angle (degrees) and pace (s/movement) are shown in figure 6. Wrist flexion angle amplitude $(F(1,4) = 40·5, p < 0·01)$ and pace $(F(4, 16) = 57·1, p < 0·001)$ were significant main effects. No significant interaction between wrist flexion angle amplitude and pace was observed $(F(4, 16) = 0·9, p > 0·1)$.

Pace was converted into frequency (Hz) by taking its inverse. A linear polynomial regression model for log transformed discomfort, fitted against the logarithm of wrist flexion amplitude, $\log A$ and the logarithm of frequency, $\log F$ was produced resulting in:

$$D = 10^{(-0·43 + 0·37 \log F + 0·70 \log A)} - 1$$

$(R = 0·97, F(2,7) = 61·1, p < 0·001)$, where D is discomfort (scale of 0 to 10), F is frequency (Hz), and A is the wrist flexion angle amplitude (degrees). The transformed data and the resulting regression relationship is plotted in figure 7. Equal discomfort strata for wrist flexion were determined by algebraically solving the above regression
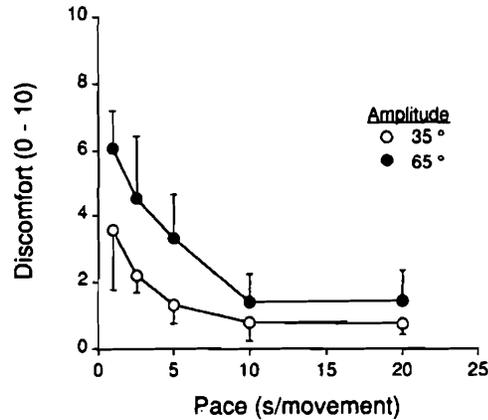
Figure 6.   Average localized discomfort response (wrist flexion) and one standard deviation (five subjects).
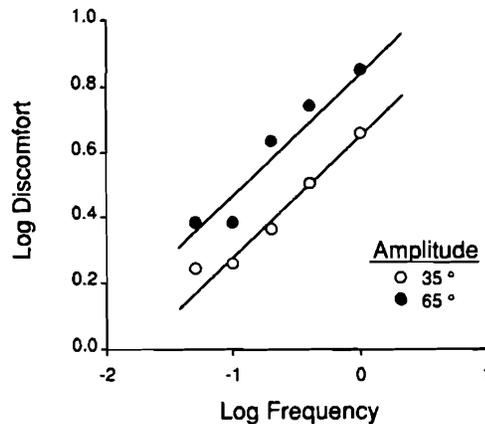

Figure 7.   Logarithm transformed localized discomfort regressed against logarithm of amplitude and frequency for controlled wrist flexion.

equation for wrist flexion amplitude angle as a function of frequency and discomfort. These strata are plotted against frequency and wrist flexion amplitude in figure 8. The curves in figure 8 indicate that according to the discomfort model level 2 discomfort for instance, occurs for repetitive wrist flexion at a frequency of 0·2 Hz and a wrist flexion amplitude of 46°, and that the equivalent discomfort level occurs at a frequency of 0·8 Hz and a wrist flexion amplitude of 22°.

The regression equation and equivalent discomfort curves were 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, derived from the inverse slope of the regression for log A and log F (see figure 7), resulted in a slope of + 10 dB/decade. The filter cut-off frequencies were arbitrarily set to the flexion amplitude that the equal discomfort curves intercept for the wrist flexion range of motion, which was considered to be 80° (see figure 8). The resulting filters were a set of high-pass filters for each discomfort level between 1 and 10 (see figure 9).
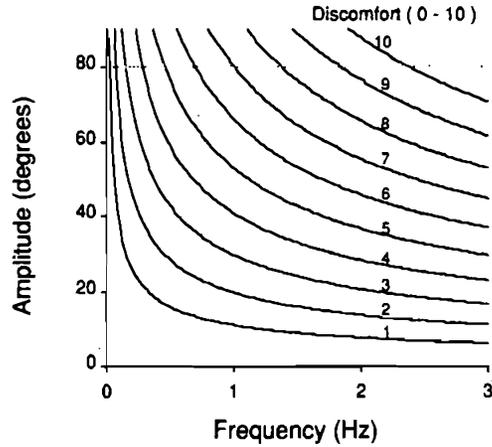
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Discomfort (0 - 10)

Figure 8. Equal discomfort strata based on solving regression equation of localized wrist flexion and discomfort. A flexion angle of 80° was considered to be the flexion range of motion limit for the wrist.
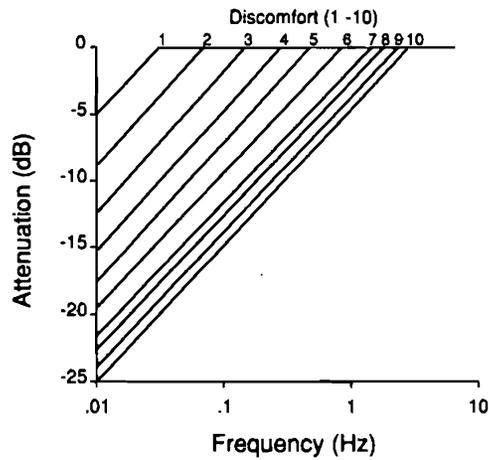
Discomfort (1 -10)

Figure 9. Frequency-weighted filters for discomfort levels 1 to 10.

Table 1. Average RMS (standard deviation in parentheses) wrist angular motion for one-hole peg task (four subjects).

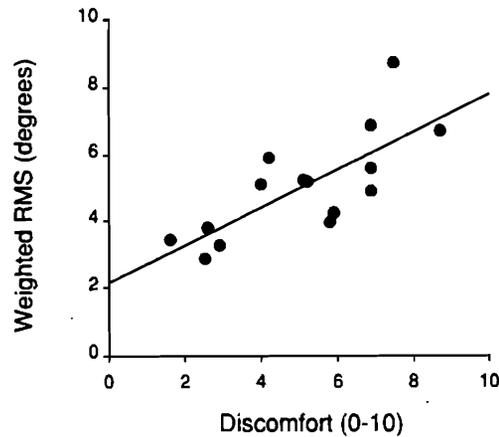| | Frequency | | | |
| | 0·2 Hz | | 0·5 Hz | |
| | Amplitude | | | |
	20°	45°	20°	45°
Average RMS wrist flexion				
Unfiltered	7·4°	14·2°	7·6°	11·6°
	(1·0)	(2·3)	(0·5)	(1·6)
Filtered	3·4°	5·5°	4·6°	7·0°
	(0·4)	(0·4)	(0·6)	(1·3)

Figure 10. Filtered RMS for wrist flexion measured using an electrogoniometer regressed against localized discomfort ratings for four subjects performing a one-hole peg transfer task.

3.2. *Frequency-weighted filter validation experiment*

The average RMS amplitude recorded for angular wrist motion in the one-hole peg task is summarized in table 1. Analysis of variance of the unfiltered RMS data indicated the amplitude effect was statistically significant ($F(1,3) = 82.4$, $p < 0.01$), but no significant effect was observed for frequency ($F(1,3) = 1.8$, $p > 0.1$). Observe that the unfiltered RMS amplitude increased as wrist flexion amplitude increased, but the unfiltered RMS amplitude was not affected by frequency (see table 1). Consequently the unfiltered RMS measure obscured the effect of frequency. The filtered RMS data, however, was statistically significant for both amplitude ($F(1,3) = 111.6$, $p < 0.01$) and frequency ($F(1,3) = 9.2$, $p < 0.05$). Hence the filtered RMS measure increased for both increasing frequency and amplitude as predicted (see table 1). No interactions between frequency and amplitude were observed for either unfiltered or filtered RMS.

Discomfort ratings for four subjects are plotted against associated weighted RMS levels in figure 10. The resulting regression equation is:

$$\hat{A} = 0.56D + 2.2$$

($r = 0.75$, $F(1,13) = 17.2$, $p < 0.001$), where $\hat{A}$ is frequency-weighted RMS angular wrist motion (degrees) and D is localized discomfort (scale of 0 to 10). A single case for one subject was omitted from the regression analysis as an outlier since the discomfort rating was greater than four standard deviations from the mean for that condition, which was attributed to carryover effect, however the outcome was unchanged when this case was included.

4. Discussion

This investigation showed that frequency-weighted filters corresponding to discomfort responses associated with controlled movements at specific frequencies and amplitudes can be developed and applied for measuring exposure to repetitive motion. Filtered wrist motion measurements were demonstrated to be proportional to localized forearm

discomfort in a simple repetitive wrist flexion task, similar to repetitive tasks often performed in industrial operations.

Experimental conditions for the frequency-weighted filter validation study were selected so that the high amplitude/low frequency and the low amplitude/high frequency conditions should result in equivalent filtered RMS levels. The outcome of table 1 confirmed this. The unfiltered RMS flexion for the high amplitude/low frequency condition was almost twice as great ($p < 0.05$) as the low amplitude/high frequency condition ($7°$ difference), but the filtered RMS levels for the same conditions were only about one degree different ($p > 0.05$), which was within the measurement error of the electrogoniometer. Although the filtered RMS wrist flexion signal was proportional to reported localized discomfort levels (see figure 10), localized discomfort ratings were probably influenced by extraneous movements in articulations adjacent to the wrist, particularly the shoulder, which were not as controlled as the wrist and may have accounted for additional sources of variance.

Marras and Schenmarklin (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 difference between these two groups. Velocity and acceleration are first and second derivatives of angular motion. Pure 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-weighting produces data in agreement with the basic findings in the study by Marras and Schoenmarklin. Furthermore, the scaling used for frequency-weighted wrist flexion measurements can indicate exposure magnitude on a scale proportional to relative discomfort.

The results obtained in this study were limited to wrist flexion motion and localized discomfort. It is anticipated that this theory is applicable to motion measured at articulations other than the wrist. Discomfort experiments similar to the one performed are needed for obtaining equal discomfort relationships for adjacent articulations, including the elbow and shoulder. It is also anticipated that the described method can be suitable for reducing continuous data for mechanical moments at the joints, provided suitable force measurement methods become available. Inclusion of force measurements only requires additional entries to the E_{mn} array. The interaction between force and repetitive motion are now being studied so that these effects can be incorporated into the exposure analysis.

Biomechanical data segments for cyclical work can be averaged element by element after being transformed into the frequency domain, having the advantage of being independent of phase. Breaking down complex tasks into elements also makes it possible for analysis to identify the most stressful aspects of complex jobs. Although this methodology greatly reduces continuous biomechanical measurements into a single quantity, a measure is still produced for every articulation, which includes at least 14 quantities for movements of the upper extremities. Since it is likely that physical stress affects different parts of the body differently, that approach seems to be reasonable. It may also facilitate targeting engineering control decisions by indicating the body part most affected by physical stress for a particular job. If necessary, further detail can be analysed by studying data for separate elemental and articular measurements.

The exposure analysis method proposed in this paper is theoretical and needs to be fully validated under actual work conditions before proven practical. As for all

applications of spectral analysis and time-weighted averaging, these methods are limited to general assumptions of linearity and stationarity of the input signals. Potential nonlinear responses to physical stress exposure were ignored. Since no interactions were observed between frequency and amplitude in the discomfort experiments, a linear model for the limited conditions studied was appropriate. Effects of duration were not addressed in this study. Assumptions about linear temporal effects for exposure to different levels of physical stress need to be tested in controlled laboratory and field studies before the proposed exposure assessment method is valid. Future applications of this methodology may be limited by deviations from these assumptions.

Another limitation of this study is that equivalent discomfort curves were generated from a very small data set. Discomfort data was collected for only one hour of work. Caution should be taken not to extrapolate this data outside its range. More detailed discomfort data is now being obtained over greater movement amplitudes and frequencies. This additional data may subsequently alter the shape of the equal discomfort curves in figure 8, and change the corresponding filter characteristic in figure 9. The limited data provided here is intended for demonstrating and testing the feasibility of this exposure analysis approach, and should be treated accordingly.

Upper extremity musculoskeletal disorders 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 physical stress in 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 determined or practically applied. The method described in this paper may make it possible to ultimately establish quantitative exposure limits.

A frequency-weighted filter function could be based on the inverse frequency characteristics of provisional exposure limits. For example, highly repetitive movements are associated with a greater risk of incurring an injury, than for less repetitive motions (Silverstein *et al.* 1986). Since high frequency motions are generally considered to be more hazardous, it was expected that the frequency-weighted filter function should be a high-pass filter, counting high frequency motions more heavily than low frequency motions. Frequency-weighted filters associated with specific movements at different frequencies and magnitudes should be developed corresponding to musculoskeletal disorder occurrence in order to produce quantitative exposure limits.

Although this study was limited in scope, it demonstrated the feasibility of using this exposure assessment approach. The actual parameters for frequency-weighted functions may be based on (1) epidemiological data, (2) biomechanical data, or (3) psychophysical data. At present, none of these relationships are known precisely and should be the subject of future research.

References

ARMSTRONG, T. J., FOULKE, J., JOSEPH, B. and GOLDSTEIN, S. 1982, An investigation of cumulative trauma disorders in a poultry processing plant, *American Industrial Hygiene Association Journal*, **43**, 103–116.

MARRAS, W. S. and SCHOENMARKLIN, R. W. 1993, Wrist motion industry, *Ergonomics*, **36**, 341–351.

MOORE, A., WELLS, R. and RANNEY, D. 1991, Quantifying exposure in occupational manual tasks with cumulative trauma disorder potential, *Ergonomics*, **34**, 1433–1453.

NIEBEL, B. W., 1988, *Motion and Time Study*, 8th edn. (Irwin, Homewood, IL).

OPPENHEIM, A. V., WILLSKY, A. S. and YOUNG, I. T. 1983, *Signals and Systems* (Prentice-Hall, Englewood Cliffs, NJ).

RADWIN, R. G. and LIN, M. L. 1993, An analytical method for characterizing repetitive motion and postural stress using spectral analysis, *Ergonomics*, **36**, 379–389.

RADWIN, R. G. and YEN, T. Y. 1993, Development of an instrument for assessing exposure to physical stress in repetitive manual work. *Proceedings of the 1993 NSF Design and Manufacturing Systems Conference, Society of Manufacturing Engineers*, 1151–1158.

SILVERSTEIN, B. A., FINE, L. J. and ARMSTRONG, T. J. 1986, Hand wrist cumulative trauma in industry, *British Journal of Industrial Medicine*, **43**, 779–784.