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Characterization of Posture, Force, and Repetitive Motion

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List of Abbreviations

AC – Alternating Current

ADL – Activities of Daily Living

ANOVA – Analysis of Variance

CTD – Cumulative Trauma Disorder

DC – Direct Current

Ext. – Extension

FFT – Fast Fourier Transform

FIR – Finite Impulse Response

Flex. – Flexion

RMS – Root Mean Square

ROM – Range of Motion

s.d. – Standard Deviation

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Significant Findings

This project developed and investigated new methodologies for analyzing continuous physical stress measurements and for quantifying exposure to physical stress. Spectral analysis was demonstrated useful for characterizing continuous records of repetitive wrist motion in cyclical tasks. Spectrum magnitudes correspond to joint excursion magnitudes at a particular frequency such that:

- Spectrum DC components quantify average sustained posture
- Spectrum frequencies quantify the rate of repetition
- Spectrum magnitude indicates postural deviation for corresponding repetition rates

An efficient method for reducing continuous biomechanical data into a quantifiable metric that accounts for recognized musculoskeletal disorder exposure factors, including repetitiveness, posture or forceful exertions, and duration was developed and shown promising as an exposure assessment strategy. A frequency domain approach was used for averaging elemental data recorded for repetitive cycles. Frequency-weighted filters enabled continuous biomechanical data to be filtered and integrated, resulting in a single quantity corresponding to psychophysical response characteristics for repetitive motion stress. Parameters for frequency-weighted filters were developed from psychophysical data for equivalent discomfort levels resulting from repetitive movements of different amplitudes and frequencies.

Field studies of selected industrial sites were performed to demonstrate that spectral analysis was capable of quantifying upper limb repetitive motion, posture, and force.

Usefulness of Findings

The ability to continuously acquire biomechanical stresses including posture and force, more accurately and precisely than classification systems, far surpasses [redacted] the availability of analytical methods for quantifying exposure. The new methods investigated in this project provide an efficient approach for quantifying the magnitude, repetitiveness, and duration of exposure to physical stress. Furthermore, this research provides evidence that such exposure assessment methods may be useful for reducing complex data into a single metric that accounts for recognized musculoskeletal disorder exposure factors.

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 sound level meters are used for measuring exposure to acoustic noise. 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.

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 methods developed in this research may make it possible to ultimately establish quantitative exposure limits.

Abstract

The availability of small, inexpensive electrogoniometers has made wrist posture measurement during repetitive manual work practical. Efficient analytical methods, however, are not currently available for quantifying the degree of repetitiveness and the interaction with postural stress. This project investigated new analytical methods for assessing physical stress exposure. A quantitative exposure assessment strategy for physical stress associated with repetitive manual tasks was developed using continuous biomechanical data measured directly from electrogoniometers or force sensors. An efficient method is described 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.

Spectral analysis was investigated as a method for characterizing repetitive wrist motion and postural stress using a simple peg transfer task. Wrist posture was controlled by adjusting the pegboard location and by having subjects reach over an obstruction. Work pace was externally controlled using an auditory signal. Angular wrist flexion/extension and ulnar/radial deviation was recorded using a 60 Hz sample rate. Power spectra were computed by stratifying data segments into individual work elements, divided by break points associated with the task. Peak spectral magnitudes and frequency components corresponded closely with joint displacement amplitudes and repetition rates. Spectrum DC component magnitudes were directly related to sustained wrist postures.

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

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 analysts to identify the most stressful aspects of complex jobs.

The relative effects of repetition, force and posture were studied in order to investigate how biomechanical measurements can be combined into a single metric corresponding to an index of strain such as subjective discomfort. A full factorial experiment was conducted involving repetitive wrist flexion from a neutral posture to a given angle against a controlled force. Seven subjects performed the task using two paces (3 s/motion and 15 s/motion), two force levels (15 N and 45 N) and two angles (15° and 45°) for one hour each. Discomfort was reported on a 10 cm visual analog scale anchored between "no discomfort" and "very high discomfort". Repeated measures analysis of variance showed that all main effects were statistically significant ($p < .05$) and no interactions were observed. A linear regression model was fit to the data and used for generating frequency weighted digital filters for quantifying repetitive motions and exertions proportional to relative discomfort. The resulting high-pass digital filter had a 22 dB/decade attenuation slope. A simulated industrial task for validating the model involved repetitively transferring pegs across a horizontal bar and inserting them into holes against a controlled resistance. Angular wrist data were recorded using an electrogoniometer and filtered. Six subjects performed the task for three conditions consisting of (1) 15° wrist flexion, 15 N resistance and 10 s/motion, (2) 15° wrist flexion, 45 N resistance and 5 s/motion, and (3) 45° wrist flexion, 45 N resistance and 4 s/motion. Discomfort was reported on the same scale after performing the task for one hour. Pearson correlations between subjective discomfort ratings and the integrated filtered biomechanical data for individual subjects ranged from 0.917 to 0.999 . The pooled correlation across subjects was 0.733. This approach may be useful for physical stress exposure assessment and for design of tasks involving repetitive motions and exertions.

1. An analytical method for characterizing repetitive motion and postural stress using spectral analysis

1.1. Introduction

Upper extremity cumulative trauma disorders (CTD) are associated with repeated movements of the body and sustained postures (Hymovich & Lindholm, 1966; Jensen, et al., 1983; Silverstein, Fine & Armstrong, 1986; and many others). Extreme joint angles are also widely recognized CTD risk factors (Younghusband & Black, 1963; Herberts, et al., 1981). Nevertheless, adequate exposure assessment methods for postural stress and repetitive motion 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 applied.

Although posture classification systems have been shown useful for studying postural stress and repetitive motion in field studies (Priel, 1974; Karhu, et al., 1977; Corlett, et al., 1979; Armstrong, et al., 1979; Armstrong, et al., 1982; Keyserling, 1986), they are extremely limited in their ability to fully characterize these stresses. They lack resolution, take a significant amount of time, require highly trained observers, and are dependent upon the analyst's experience and biases. This has led investigators to search for suitable automated analysis techniques.

The small, relatively inexpensive electrogoniometers that are now commercially available can continuously measure repetitive hand motion in manual tasks. Although these instruments can more accurately and precisely measure movements than classification methods, these systems can produce abundant amounts of data quite rapidly. Hence efficient methods are needed for reducing these large quantities of data into a usable form.

Repetitive motion arises from the cyclical nature of manual work in modern industry. The metric called "repetitiveness" is often related to the frequency, or the number of cycles per unit time, that specific motions occur in an arbitrary work period (Armstrong, et al., 1982; Silverstein, et al., 1986). Articular angles in repetitive tasks are repeated cyclically, or they are maintained for long periods of time. The magnitude of postural changes, and the frequency which they repeat throughout the work cycle, comprise dynamic patterns of motion. Kinematic recordings of wrist articulation angles produce complex waveforms representing these motion patterns.

This paper investigates use of spectral analysis for characterizing repetitive motion performed in cyclical tasks. It is hypothesized that if the associated power spectrum magnitudes correspond to joint excursion angles at a particular frequency of repetition then the degree of postural stress and repetitiveness will be indicated by the spectrum frequency components such that:

1. The DC component of the spectrum is a metric of postural stress and indicates the average sustained posture.

2. The AC frequency components of the spectrum are related to the rate of repetitive movements.

3. The magnitude of each spectral component indicates postural deviation for its corresponding repetition rate.

1.2. Methods

Dependent variables in this study included wrist flexion/extension and ulnar/radial deviation angles. A Penny and Giles Biometrics model M110 strain gage wrist goniometer was fastened across the wrist on the dorsum of the hand and forearm using two-sided tape. Neutral wrist flexion/extension and ulnar/radial deviation were set as zero degrees and were determined by placing the forearm and hand against a flat horizontal surface, and resting the fingers on a wedge. Active range of motion (ROM) for wrist flexion/extension and ulnar/radial deviation were also determined. A MacAdios 12-bit analog-digital converter and Macintosh II/fx microcomputer were used for sampling the electrogoniometer output signals. The angular resolution was limited by the measurement error of the goniometer, which the manufacturer specified as 1°. By convention, wrist flexion and ulnar deviation were positive, and wrist extension and radial deviation were negative with respect to neutral posture.

The experimental apparatus consisted of two 4×4 peg boards (see Figure 1.1). The peg boards were either located adjacent to each other or they were placed on two shelves that were independently adjustable in height. The angle of inclination was independently adjusted for both peg boards. The lower peg board was located near elbow height for each subject so that a neutral wrist posture was assumed when grasping a peg using a pinch grip. The upper shelf height was adjusted to approximately shoulder height. A horizontal bar was located in front of the upper peg board so wrist flexion angle may be controlled (see Figure 1.1).

An electronic timer produced a periodic tone for pacing the task. All peg transfers were performed with the dominant hand using a natural motion. The order that experimental conditions were presented was counterbalanced among subjects. A three minute rest period was provided between every set. Two learning sets were performed prior to collecting data.

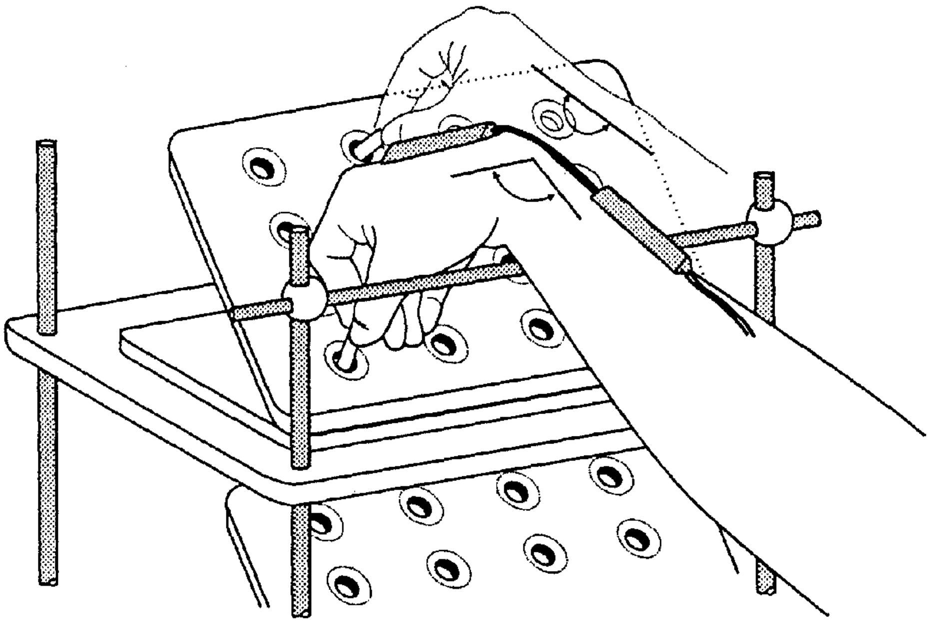

Figure 1.1: Experimental apparatus including two 4 × 4 peg boards located on two adjustable height shelves. The inclination angles were also adjustable and a bar was located in front of the upper peg board for controlling wrist flexion angle. Flexion angle increased when grasping pegs from Row 1 to Row 4.

In this paper, the term *element* is defined as the set of movements contained between two arbitrary, but distinct break points associated with a task. A *cycle* is a series of motions that are performed repeatedly. When a series of movements that are performed repeatedly are part of a cycle, they are called *subcycles*. Subcycles can sometimes be combined into longer subcycles. When a series of repetitive movements, or subcycles, are combined until they cannot be combined any further, it is called a *fundamental cycle* .

Cycle time, T_C, depends upon the nature of the work, normally ranging from several seconds to hours for industrial operations. When continuous posture data is digitized into discrete data samples, the sampling period T_S should be long enough to contain at least one cycle such that $T_S \geq T_C$. The spectrum frequency bandwidth must be large enough to include the highest frequency of articular motion for the task. The frequency resolution has to be small enough to discriminate variations in task subcycle times. Hence the frequency resolution is determined using the relationship, $\Delta f \leq 1/T_C$. The sample rate F_S must be high enough to avoid aliasing. A 60 Hz sampling rate was selected for this study, providing a Nyquist frequency of 30 Hz.

Several assumptions are necessary for using discrete sampled postural data for estimating power spectra. The cyclical nature of articular movements in repetitive tasks conveniently fits the FFT assumption that the signal is periodic (Oppenheim, et al., 1983). By breaking down repetitive movement data segments into individual elements, similar to a time-and-motion study elemental analysis, the resulting data segment may then be considered periodic for the movements confined within that element. Another assumption that must be satisfied is that the signal be stationary and linear. A signal is stationary if it has a power spectrum that does not change with time. Onset of fatigue, for instance, may affect movements this way. As a practical matter, it is sufficient that the signal does not change during the sample period (Beranek, 1971). It is therefore reasonable to assume that for brief recording periods, fatigue onset will not significantly affect the movement.

Sampled posture data were divided into segments L points in length, corresponding to individual elements. A Hanning window was then applied to the time series data in order to prevent leakage, or end-point effects. The windowed data was then packed into a vector N points in length, where N ≥ L, and padded with zeros. This process is described by the following expression:

$$\hat{a}_i = \begin{Bmatrix} \frac{a_i}{2}\left(1-\cos\frac{2\pi i}{L}\right), & \text{if } i = 1,\ldots,L \\ 0, & \text{if } i > L \end{Bmatrix}, \text{ for } i = 1,\ldots,N$$

where $a_i = i_{th}$ sample of joint angle $a(t)$.

The discrete Fourier transform of $\hat{a}_i$ was computed using a mixed radix FFT algorithm. The resulting complex transformation record was multiplied by its complex conjugate and divided by the square of the number of data points to compute the power spectral density magnitude A_i^2 such that:

$$A_i^2 = \frac{1}{N^2}\left|\sum_{k=1}^{N} \hat{a}_k e^{\frac{-j2\pi ik}{N}}\right|^2, \text{ for } i = 1,\ldots,N$$

where $j = \sqrt{-1}$.

The average amplitude spectrum, $\overline{A}_i$, for M replicates of an element was computed using ensemble averaging in the frequency domain , where:

$$\overline{A}_i = \begin{Bmatrix} \sum_{k=1}^{M} \frac{\sqrt{A_{ik}^2}}{M}, & \text{if } i = 1 \\ \sum_{k=1}^{M} \frac{\sqrt{2A_{ik}^2}}{M}, & \text{if } i \geq 2 \end{Bmatrix}, \text{ for } i = 1,\ldots,\frac{N}{2}$$

1.3. Results and Discussion

1.3.1. Experiment 1: Simple Peg Transfer from the Upper to the Lower Peg Board

This experiment consisted of transferring pegs from the upper peg board to the lower peg board, involving primarily wrist flexion/extension. The height of the bar placed in front of the upper peg board, and the peg board inclination angle were adjusted for each subject so the wrist flexed between 75% – 80% ROM when reaching for pegs in the bottom row (Row 4), and 0% – 5% ROM when reaching for pegs in the top row (Row 1). The lower peg board didn't have an obstruction and its angular position and vertical location were adjusted so the pegs can be reached using neutral wrist flexion/extension. The task was performed for two paces (5 s/peg and 2.5 s/peg).

A cycle consisted of transferring a peg from one peg board to the other. The basic movements in a cycle included:

Reach for peg
Grasp peg
Move peg
Position peg
Release peg

Wrist angle data was divided into four elements, each consisting of transferring all four pegs from one of the four rows. Therefore each element contained four cycles. The sampling period $T_S = 80$ s for the slow pace (5 s/ peg) and $T_S = 40$ s for the fast pace (2.5 s/ peg). The frequency resolution was fixed at $\Delta f = 0.086$ Hz for a 30 Hz bandwidth. Five subjects performed four replicates of each element for both paces.

A segment of wrist flexion/extension time series data and the associated power spectrum for the two paces are included in Figure 1.2. The spectrum fundamental frequency corresponded to the reciprocal of the pace (1/5 s/peg = 0.2 Hz and 1/2.5 s/ peg

= 0.4 Hz), within the spectrum frequency resolution. Similar results were observed for all subjects. The mean magnitude for five subjects at the fundamental frequency was 6.3° (SD = 1.0°), which significantly ($F(1,8)=15.07$, $p<.01$) reduced 5 dB to 3.7° (SD = 1.1°) for the first harmonic (0.4 Hz for the slow pace, and 0.8 Hz for the fast pace).

The power spectrum fundamental frequency magnitude, averaged over two paces and stratified by row for five subjects, is plotted in Figure 1.3. Full factorial repeated measures analysis of variance indicated that the magnitude increased significantly as row changed from the top row to the bottom row ($F(3,12)=30.6$, $p<.001$). This effect was also significant ($p<.001$) when independently computing the magnitude for each of the five subjects. Pair-wise Tukey contrasts between the four row spectrum fundamental frequency magnitudes were all significant ($p<.05$), except for the difference between Row 1 and Row 2. No significant ($p<.1$) magnitude effects were observed for pace, or for the interaction between pace and row.

The power spectrum fundamental frequency corresponded to the fundamental cycle repetition frequency, within the frequency resolution of the spectrum. Although higher harmonics were present, these components were at least 5 dB less in magnitude and were apparently associated with smaller but repetitive movements contained within a cycle (See Figure 1.2). For instance, the wrist flexed when grasping the peg from the upper peg board and flexed again when positioning the peg in a hole on the lower peg board. Spectrum fundamental frequency magnitudes were able to resolve differences in postural changes between different peg board rows. This method was not only demonstrated useful for measuring the rate of repetition, but for indicating the magnitude of postural stress for movements at each repetition rate.

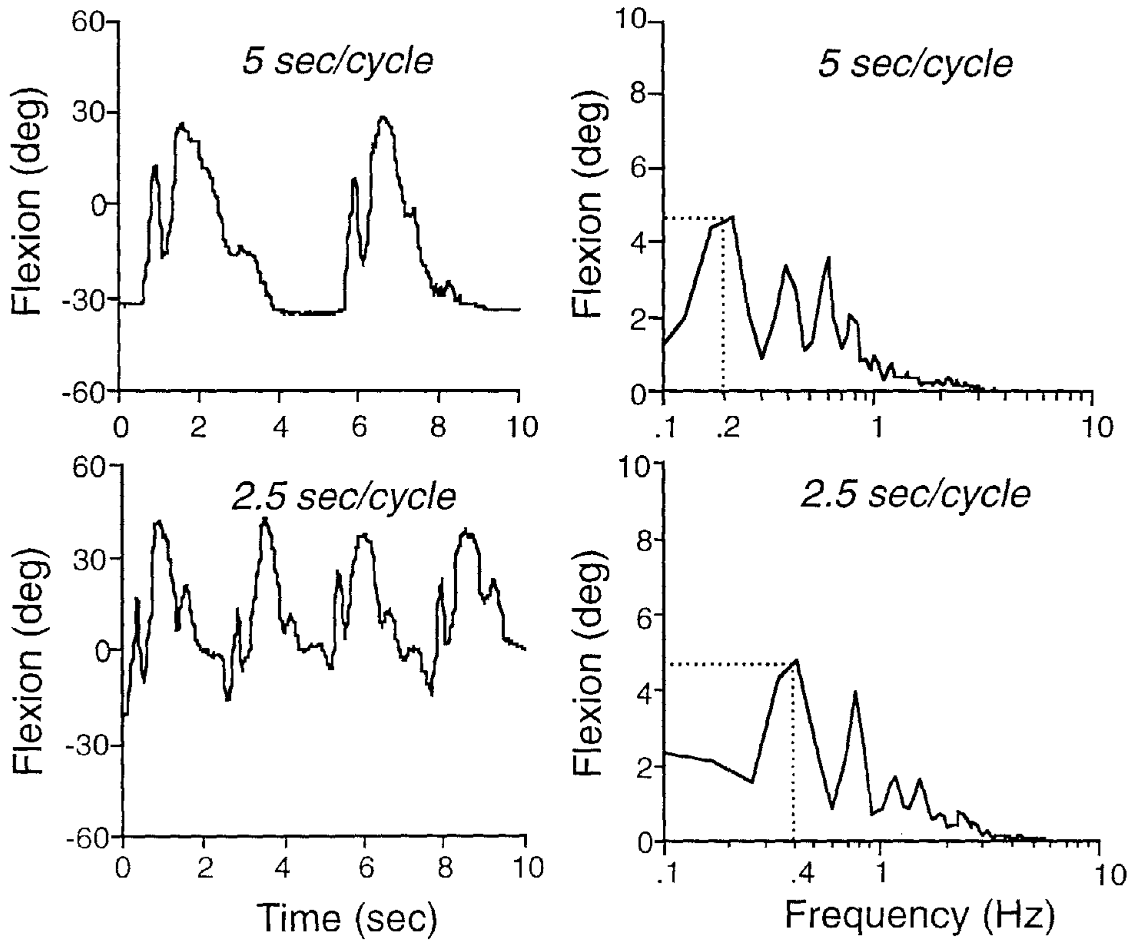

Figure 1.2: Representative time series and spectra for transferring pegs at two paces (1 subject). The fundamental frequency and its associated harmonics doubled from 0.2 Hz to 0.4 Hz as pace increased from 5 s/cycle to 2.5 s/cycle.

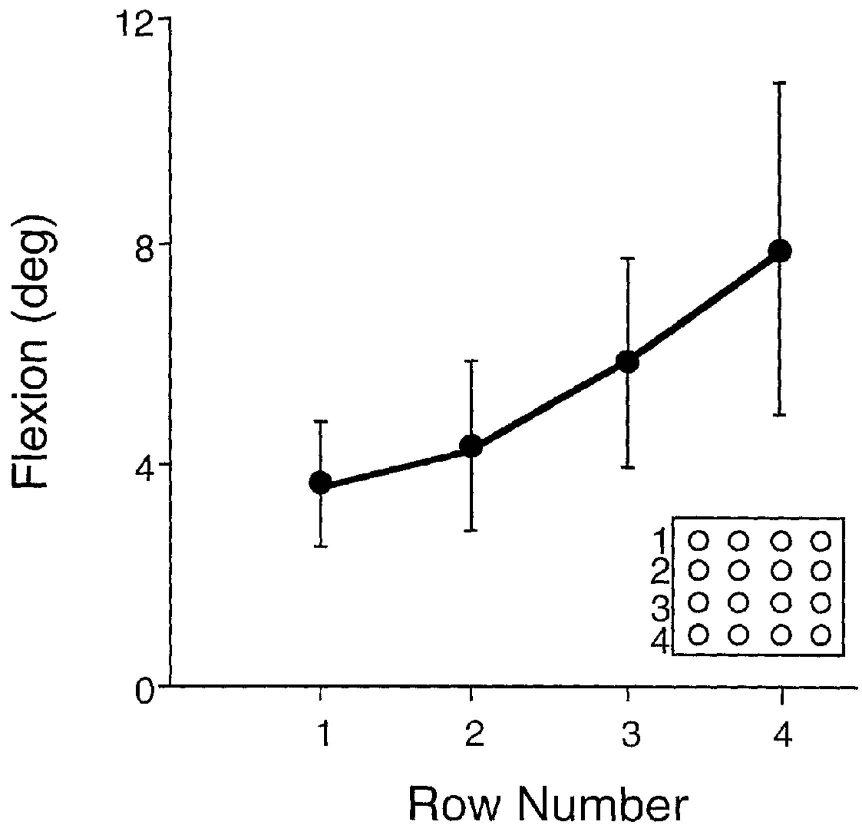

Figure 1.3: Average fundamental frequency magnitude for each element increased as wrist flexion angle increased, when grasping pegs from Row 1 to Row 4 (5 subjects). Error bars indicate one standard deviation.

1.3.2 Experiment 2: Lateral Peg Transfer on the Same Peg Board

This experiment involved repetitive ulnar/radial deviation while sustaining constant wrist flexion. The task required transferring pegs laterally over two holes on the peg board in the same row (i.e. Column 3 to Column 1, and Column 4 to Column 2) of a peg board. The basic movements in a cycle were:

$$\left.\begin{array}{c}\text{Reach for peg}\\ \text{Grasp peg}\\ \text{Move peg}\\ \text{Position Peg}\\ \text{Release peg}\end{array}\right\}$$

There were four elements for this task consisting of transferring two pegs in each row. Five subjects performed four replicates of each element for one pace (1.2 s/peg). This task was performed with a horizontal bar in front of the peg board in order to induce wrist flexion, and without a bar. The two dependent variables for this experiment included wrist flexion/extension angle and ulnar/radial deviation angle. The sampling period T_s = 10 s, and the frequency resolution was Δf = 0.059 Hz for a 30 Hz bandwidth.

Spectra for wrist flexion/extension and ulnar/radial deviation, plotted on a linear abscissa and including the DC component (0 Hz), are shown in Figure 1.4. Wrist flexion/extension was sustained throughout the task when the obstruction bar was present. This effect is clearly indicated by observing the difference in the DC component magnitudes for flexion/extension when the obstruction was, and was not present (See Figure 1.4). The average flexion/extension DC component magnitude significantly increased 10 dB from 2.8 ° (SD = 2.0°) without the bar, to 9.2° (SD=6.4°) when the bar was in place ($F(1,4)=23.54$, $p<.01$). The fundamental frequency mean magnitude increased from 2.5° (SD=1.6°) for Row 1 to 18.0° (SD = 3.1°) for Row 4 ($F(3,12)=34.22$, $p<.001$), similar to the results obtained in Experiment 1, when the obstruction bar was present. No significant effect was observed for the average ulnar/radial deviation DC component (F(1,4)=1.05, p<.5).

These findings indicated that spectrum DC components can independently measure sustained posture while the AC components measured repetitive movements. Although eliminating the obstruction affected the DC component magnitude, due to the absence of sustained wrist flexion, ulnar/radial deviation DC components and the flexion/extension fundamental frequency magnitude were unaffected.

1.3.3. Experiment 3: Two Subcycles Contained Within a Fundamental Cycle

This task was more complex than the previous tasks. Adjacent 4 × 4 peg boards contained two consecutive rows of 16 pegs (Row 1 and Row 2). The task involved transferring two adjacent pegs from Row 1 to Row 3, followed by transferring two additional pegs from Row 2 to Row 4 from the same columns, respectively, as the previous two pegs were transferred. Hence there were two subcycles contained within the fundamental cycle. These subcycles were repeated two times each for every fundamental cycle.

The basic movements in a fundamental cycle for this task contained the following motions:

$$\left.\begin{array}{l}\left.\begin{array}{l}\text{Reach for Peg}\\\text{Grasp Peg}\\\text{Move Peg}\\\text{Position Peg}\\\text{Release Peg}\end{array}\right\}2\times\\\left.\begin{array}{l}\text{Reach for Peg}\\\text{Grasp Peg}\\\text{Move Peg}\\\text{Position Peg}\\\text{Release Peg}\end{array}\right\}2\times\end{array}\right\}$$

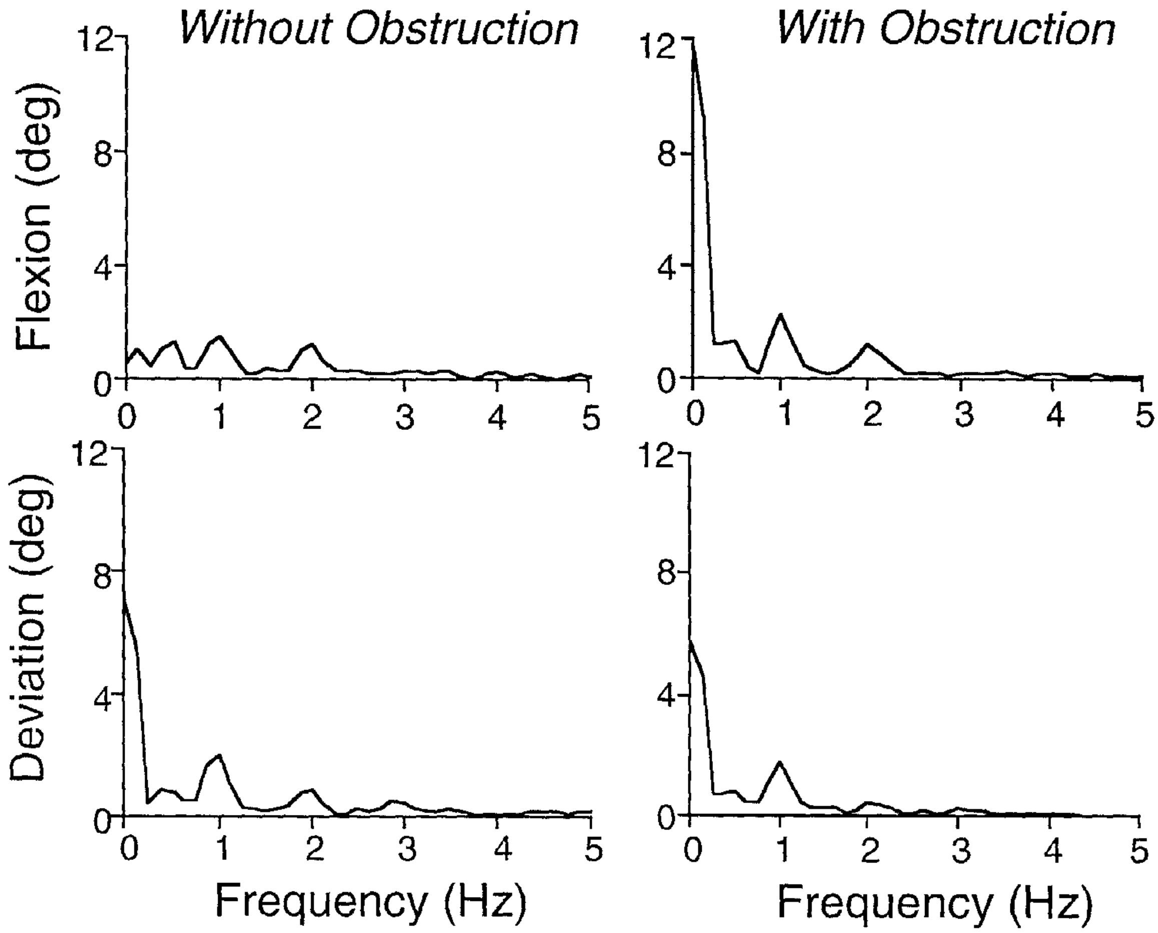

Figure 1.4: Representative spectra of wrist flexion/extension and ulnar/radial deviation (including DC component) for lateral peg transfers, both with and without an obstruction bar (1 subject). DC component magnitude for wrist flexion/extension is completely abated when the obstruction causing sustained flexion was removed.

One element, consisting of transferring all 16 pegs, was used in this analysis. Five subjects repeated four elements at a pace of 1.2 s/peg. The sampling period was $T_s = 20$ s, and the frequency resolution was $\Delta f = 0.029$ Hz for a 30 Hz bandwidth.

The resulting time series and corresponding power spectra are shown in Figure 1.5. Since a fundamental cycle contained two alternate repeating subcycles, two distinct frequencies were anticipated. This expectation was confirmed in the resulting spectrum. Because two repetitive subcycles were included in one element, they appeared as two major frequency components in the spectrum (See Figure 1.5). Spectra fundamental and higher order frequency components corresponded to repetitive motions contained in the complex element. The first peak, at a frequency of 0.21 Hz was associated with the fundamental cycle which involved transferring four pegs at a rate of 4×1.2 s = 4.8 s/cycle. The second peak, at a frequency of 0.83 Hz, was associated with the two subcycles which involved transferring pegs at 1.2 s/cycle. Note that the higher frequency peak was not a first harmonic of the lower frequency peak, but was four times the lower frequency as it was repeated in the task. No significant ($F(1,8)=1.907$, $p<.5$) differences were observed between the average magnitudes at the two peak frequencies (5 subjects). Similar results were observed for all five subjects.

Electrogoniometers have been used both inside the laboratory (Klissouras and Karpovich, 1966; Kinzel, et al., 1972; Chao, 1980; Palmer, et al., 1985) and outside the laboratory environment (Chao et al., 1980; Renfrew et al., 1984; Palmer et al., 1985; Armstrong, et al., 1985; Shoenmarklin and Marras, 1989; Moore, Wells and Ranney, 1991). They provide continuous direct measurement of body position along with repeatable measurements of joint angle, are relatively low cost and easy to use compared with classification system methods, and they avoid the requirement of being able to see a segment's position during motion. Electrogoniometers are limited to planar motions of body segments and have difficulty with complex joints such as the shoulder.

Furthermore, underlying soft tissue motion can cause them to shift in position, producing measurement errors. Attachment may also alter normal motion patterns (Chaffin and Andersson, 1984). Despite these limitations, electrogoniometer use is becoming practical for use in field studies.

A number of analytical methods have been used for evaluating repetitiveness for certain manual jobs involving the upper extremities. Armstrong, et al. (1979) obtained postural data for the hand and wrist using traditional industrial engineering elemental analysis methods based on observing cinematographic records for estimating the frequencies that various hand positions were used for sewing. Descriptive statistics, such as total time and average time spent in each posture have been used for reducing postural data (Keyserling, 1986; Wells, 1990). Keyserling (1986) combined posture classification with task analysis and time-motion study for measuring the time duration that standard postures were assumed. This analysis included classifying the sequence of postures, the total time spent in each standard posture during the work cycle, the maximum and minimum times spent in each posture during the work cycle, the number of times each posture was assumed, the percent of the cycle spent per posture, the average time per posture. While providing information about the distribution of time spent in each posture, total time gives no indication of the level of repetitiveness. Similarly, average time spent in each posture gives no indication of the number of times a certain posture is assumed. Neither can indicate the frequency distribution of postural changes.

Armstrong, et al. (1979) produced histograms for the percent occurrence of specific hand postures including pinch, opposed palm, and press. Palmer, et al. (1985) also used histograms for average wrist flexion/ extension and radial/ ulnar deviation used by 10 subjects performing 25 standardized tasks. The proportion of time that a posture is assumed, however, lacks information regarding temporal aspects of motion. Marras and Schoenmarklin (1990) produced histograms of range of motion and angular velocity, and angular acceleration of the wrist. This method, however, obscures the frequency aspects of the signal.

The idea of using spectral analysis for reducing postural data is not entirely new. Niki and Henderson (1985) studied athetotic elbow movements of cerebral palsy patients using a goniometer and frequency analysis. Mann, et al. (1989) demonstrated the utility of frequency spectral analysis for reducing wrist flexion/ extension, ulnar/ radial deviation, and forearm rotation data obtained for 24 activities of daily living (ADL). Logan, et al. (1989) used frequency analysis for identifying the dominant frequencies for simulated assembly tasks. The current study using controlled laboratory tasks demonstrated that this method can be extended and used for resolving differences in repetitiveness, postural stress, and sustained posture for specific aspects of repetitive manual tasks . Furthermore spectrum component differences were observable when making changes in a specific task requirements, or work station design.

Although awkward posture and repetitive motion has been associated with CTDs, little is actually known about the relationship between posture, repetitive motion, and the risk of injury. Keyserling (1986) pointed out that this is due to the difficulty of conducting the necessary large-scale epidemiological studies because they are prohibitively expensive due to time and effort required for evaluating postural data using conventional methods. Corlett, et al. (1979) conceded that there are few criteria available for defining adequate postures and safe exposures to such postures. They declared that the ability to measure posture far surpasses the ability to interpret the data, and that the next advances will arise only after there is a better understanding of the meaning of postural data. The current investigation advances the critical need for efficient analytical methods for quantifying the degree of repetitiveness and the interaction with postural stress.

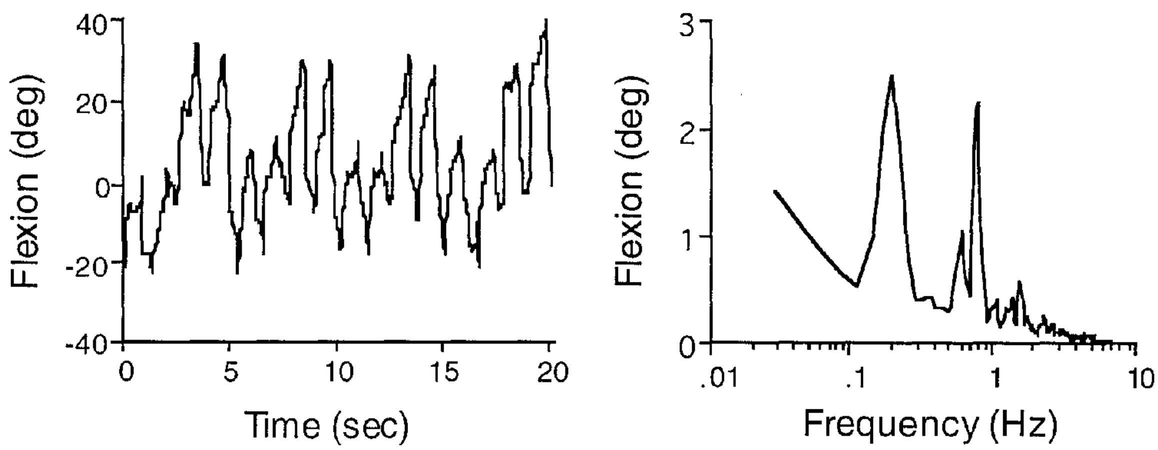

Figure 1.5: Representative time series and spectra for transferring pegs when subcycles are repeated four times within a fundamental cycle (1 subject). Spectrum contains two peaks at 0.21 Hz for the fundamental cycle repetition frequency, and at 0.83 Hz for the subcycle repetition frequency.

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

2.1. 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 a relatively small numbers of workers (Moore, Wells, and Ranney, 1991; Marras and Schoenmarklin, 1993). Video based data acquisition methods are now available for simultaneously recording biomechancial data in synchronization with video images, making it possible to record large quantities of data and interactively extracting data for analysis corresponding to specific video taped 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 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. 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 if 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.

2.2. Methods

2.2.1. *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 2.1.

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 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 elemental time, T_{E_n}. The frequency, F_{E_n} that work element E_n repeats in activity A_l (expressed in

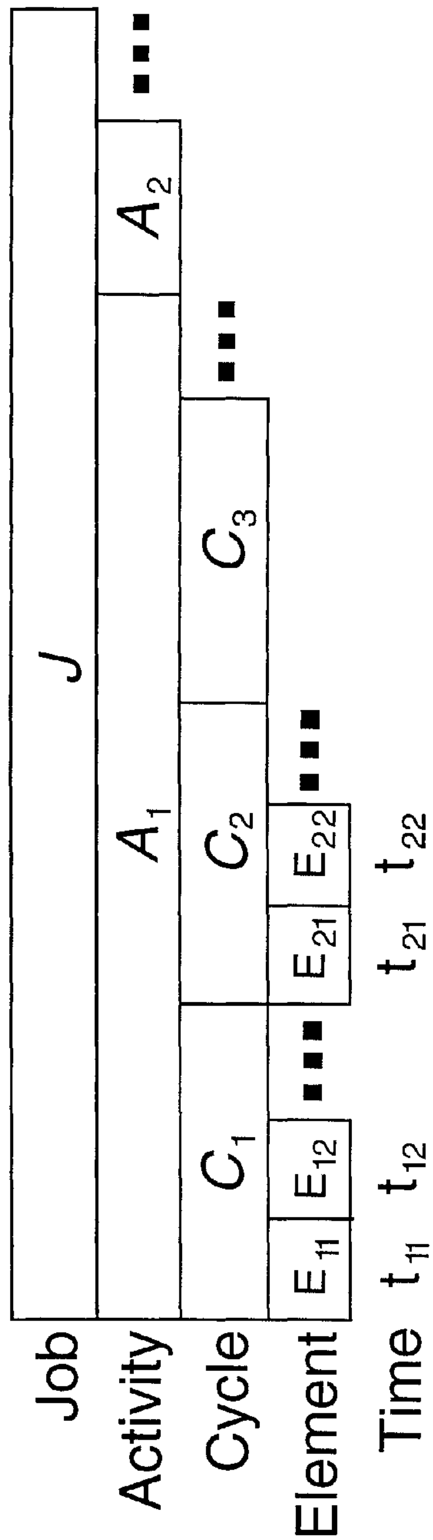

Figure 2.1. Job (J) is divided into a set of work activities (A) that consist of repeating cycles C containing elements (E). Traditional time and motion study characterizes each element by its mean elemental time (t).

terms of the number of repetitions per unit time) is sometimes estimated from the reciprocal of the cycle time, T_{Cl}, such that:

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

Cycle time has been previously used 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 which customarily involves frame-by-frame examination of a video tape, 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.

2.2.2. *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 gage wrist goniometer. The device was fastened across the wrist on the dorsum of the hand and forearm using two-sided tape.

A data recording system that records analog 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). Analog 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 onto the audio track of VHS tape together with video image. Data sampling 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 video tape and interactively identifies 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 video tape 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 Hz = 16 ms. Sampled biomechanical data can then be divided into time series segments corresponding to individual elements.

2.2.3 *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:

$$E_{mn} = \{a_{mn1}(t_j), a_{mn2}(t_j), a_{mn3}(t_j), ..., a_{mn14}(t_j)\}.$$

where:

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

for the upper extremities, and t_j are discrete time samples. The corresponding data segments are extracted using element 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 method describes 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 enables averaging elemental biomechanical data, where averaging in the time domain may not be feasible. Time averaging is not usually practical because 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 2.2).

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

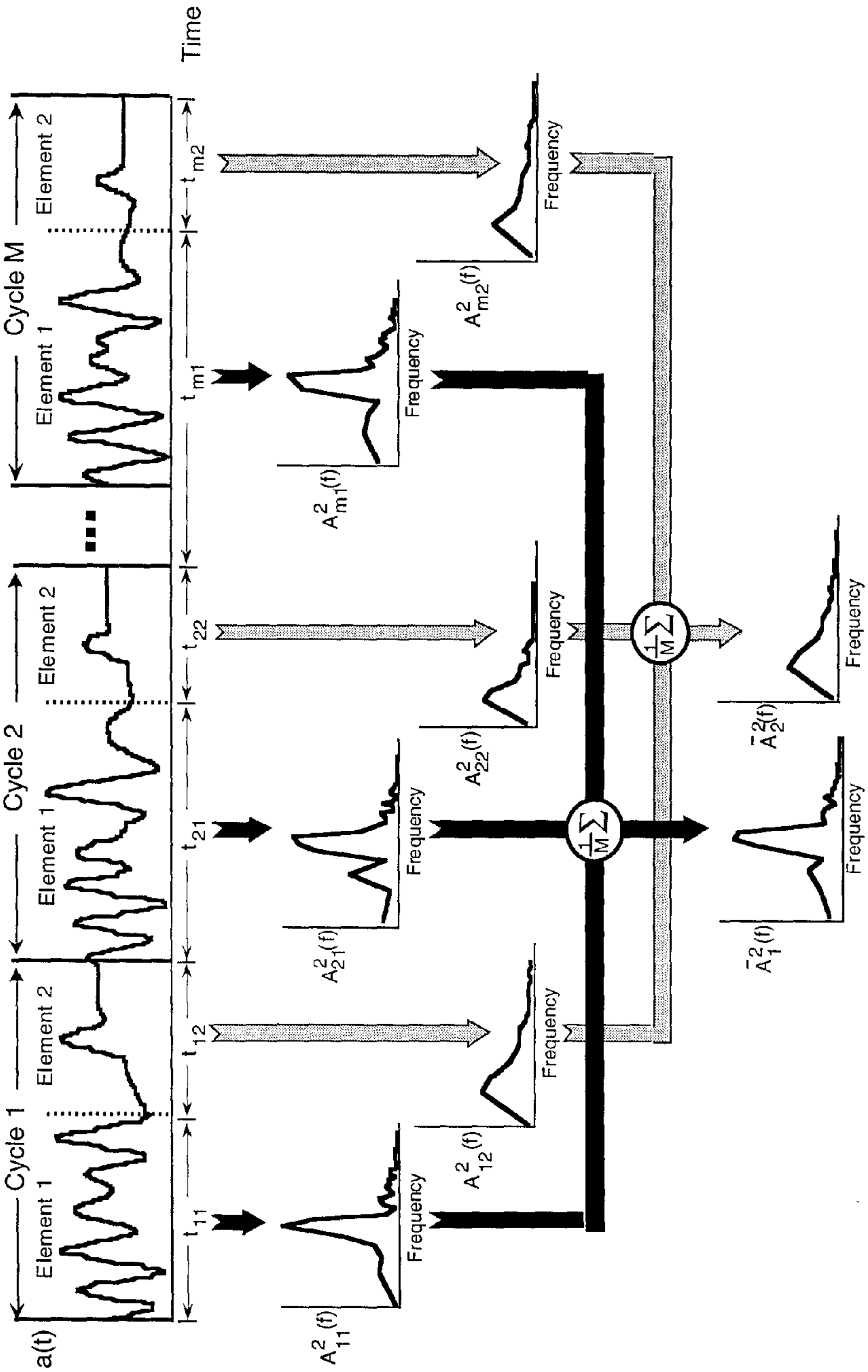

Figure 2.2. Spectra are computed for wrist flexion biomechanical time data extracted for every work element.

al., 1988). 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:

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

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

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

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

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

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

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

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

Although this approach permits averaging elemental 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 2.3 where sine

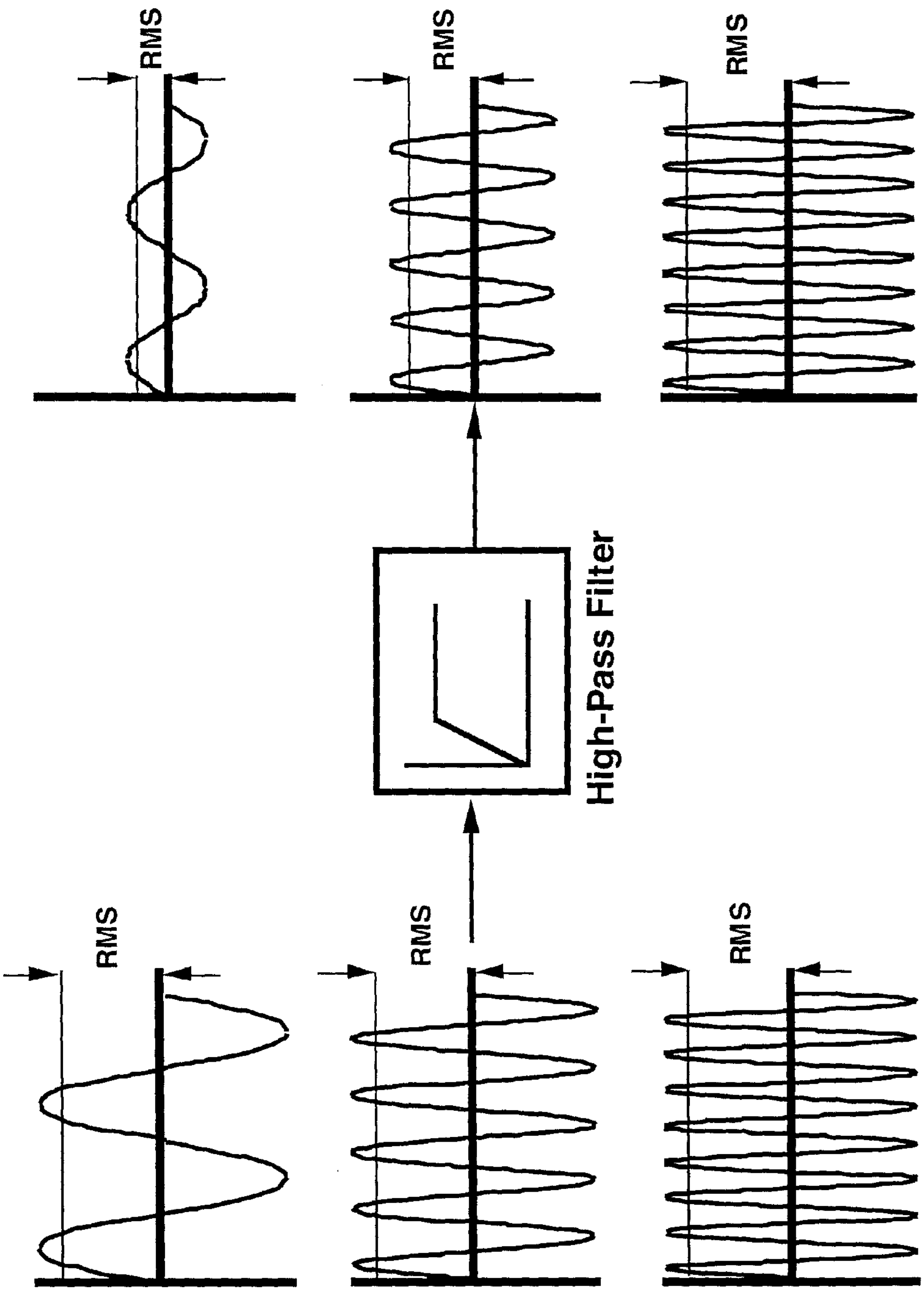

Figure 2.3. Filtered *RMS* increases with increasing frequency.

waves all having the same RMS input amplitudes 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 stress levels. This concept is illustrated in Figure 2.4 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(fk)* can be developed corresponding to physical stress frequency response, 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 $\overline{A}^2_{mni}$ 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 loosing 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 2.5.

After the integrated filtered metric is determined, exposure may be assessed 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:

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

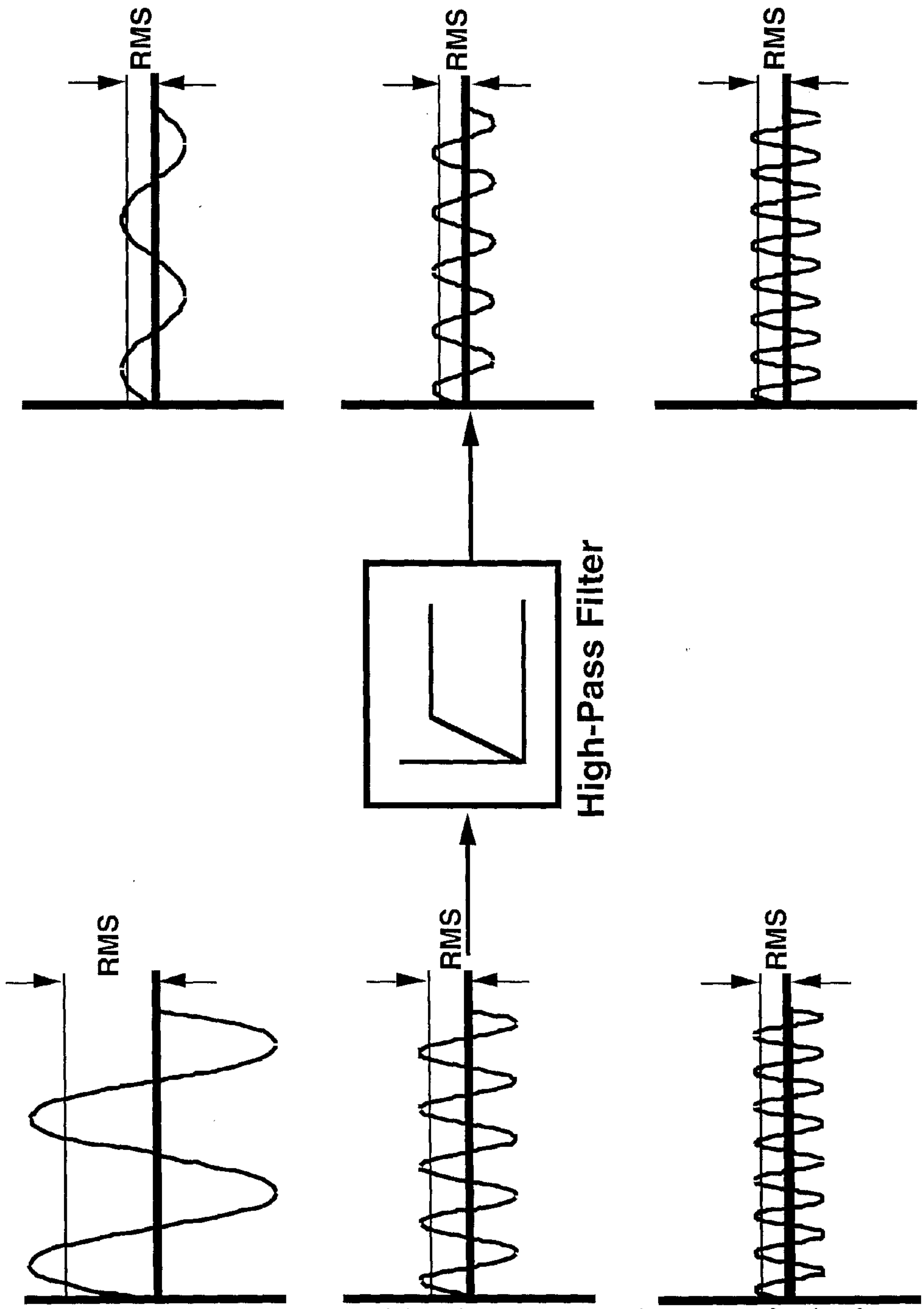

Figure 2.4. Equivalent frequency weighted filtered *RMS* remains constant for signals having amplitudes and frequencies that result in equivalent responses.

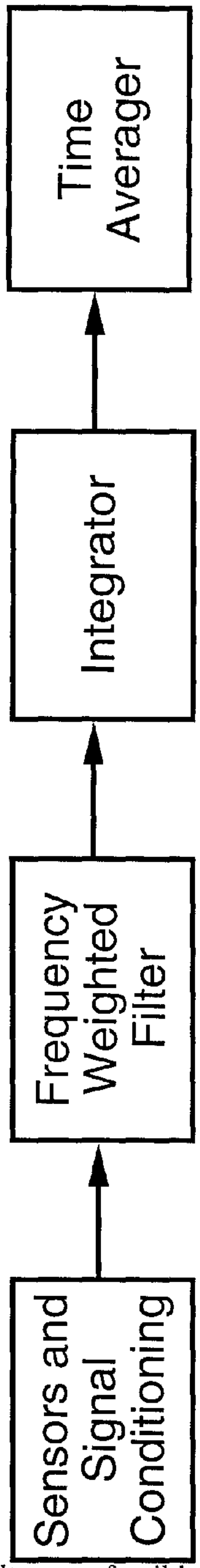

Figure 2.5. If frequency-weighted filters are feasible the basic exposure assessment instrument is simplified to the basic system shown above.

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

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

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

2.2.4 *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 center 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 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 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. The timer produced a brief tone indicating to flex the wrist 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 21 yr to 26 yr.

Discomfort was measured using the cross-modality matching method. Subjects marked localized discomfort on a visual analog 10 cm linear scale, anchored on the left as "no discomfort," and on 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 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 the Results section.

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 which was located at its center. 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 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 a low force task.

The validation experiment was a 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 subjects had to assume either a 20° or 45° wrist flexion angle when inserting pegs into the hole. The container was located so 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 training 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 21 yr to 31 yr.

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.

2.3. Results

2.3.1 *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 2.6. Wrist flexion angle amplitude ($F(1,4) = 40.5, p < .01$) and pace ($F(4,16) = 57.1$, $p < .001$) were significant main effects. No significant interaction between wrist flexion angle amplitude and pace was observed ($F(4,16) = 0.9, p > .1$).

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:

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

($r = 0.97$, $F(2,7) = 61.1, p < .001$), 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 2.7. Equal discomfort strata for wrist flexion were determined by algebraically solving the above regression 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 2.8. The curves in Figure 2.8 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 above 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

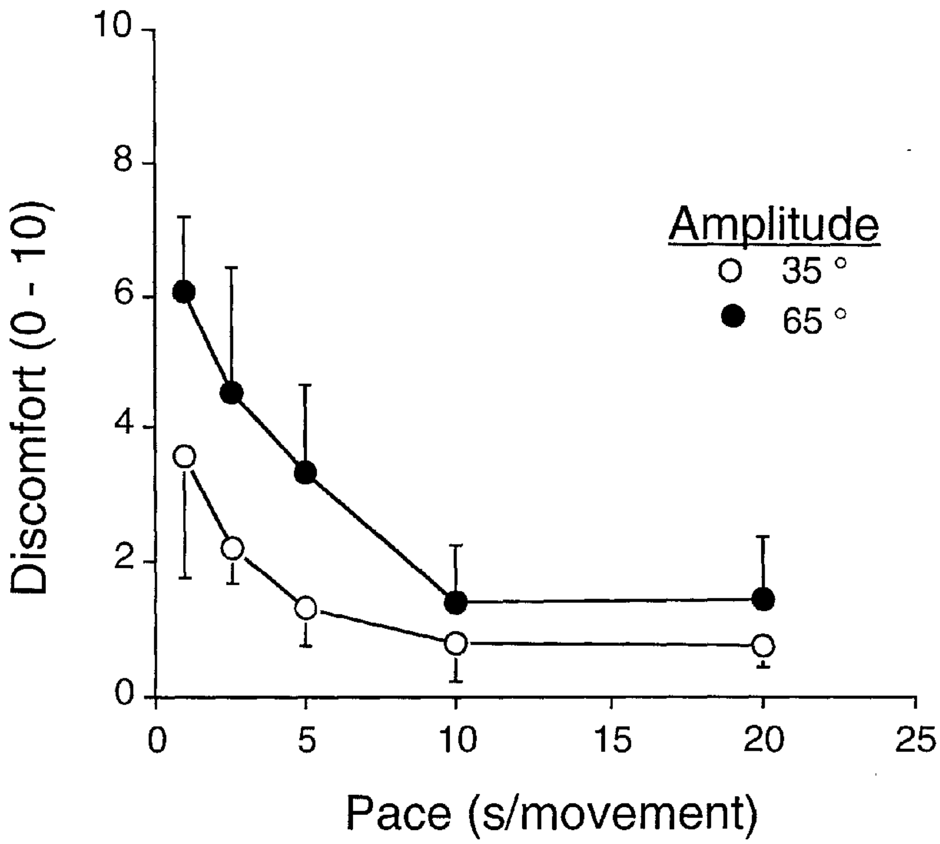

Figure 2.6. Average localized discomfort response (wrist flexion) and one standard deviation (5 subjects).

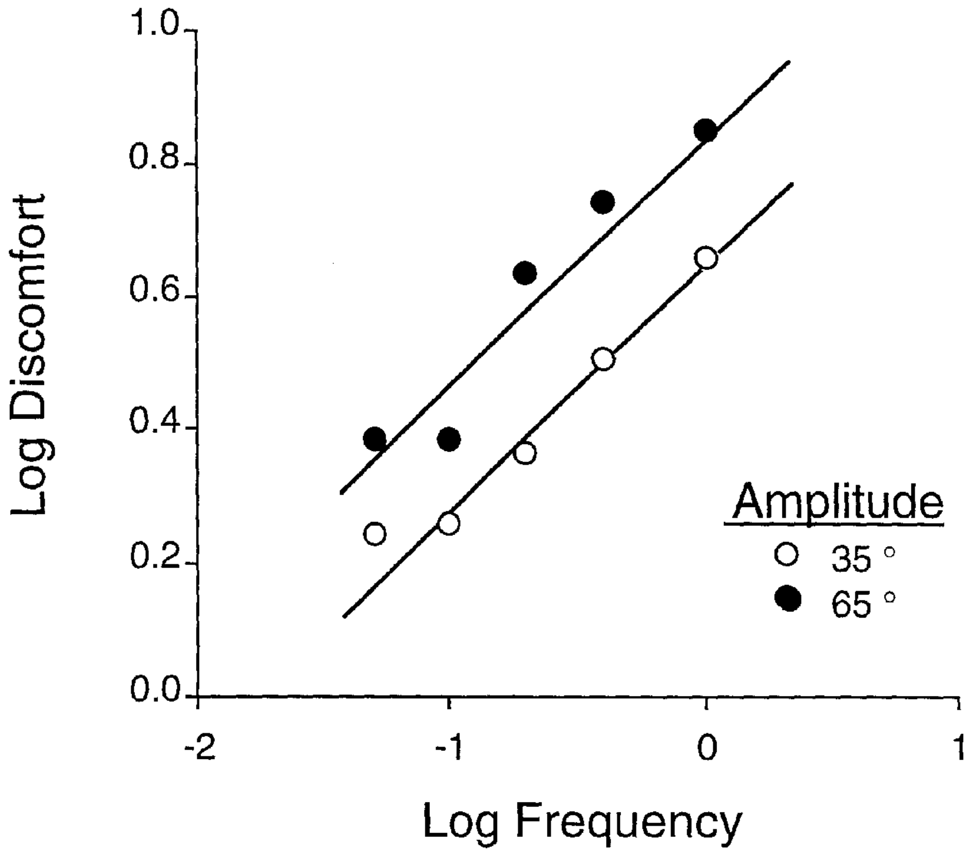

Figure 2.7. Logarithm transformed localized discomfort regressed against logarithm of amplitude and frequency for controlled wrist flexion (*r* = .97).

the inverse slope of the regression for *log A* and *log F* (See Figure 2.8), resulted in a slope of +10 dB/ decade. The filter cutoff frequencies were arbitrarily set to the flexion amplitude that the equal discomfort curves intercept for the wrist flexion range of motion, which was considered 80° (see Figure 2.8). The resulting filters were a set of high-pass filters for each discomfort level between 1 and 10 (See Figure 2.9).

2.3.2 *Frequency-Weighted Filter Validation Experiment*

The average RMS amplitude recorded for angular wrist motion in the one-hole peg task is summarized in Table 2.1. Analysis of variance of the unfiltered RMS data indicated the amplitude effect was statistically significant ($F(1,3) = 82.4, p < .01$), but no significant effect was observed for frequency ($F(1,3) = 1.8, p > .1$). Observe that the unfiltered RMS amplitude increased as wrist flexion amplitude increased, but the unfiltered RMS amplitude was not affected by frequency (See Table 2.1). Consequently the unfiltered RMS measure obscured the effect of frequency. The filtered RMS data, however, was statistically significant for both amplitude ($F(1,3) = 111.6, p < .01$) and frequency ($F(1,3) = 9.2, p < .05$). Hence the filtered RMS measure increased for both increasing frequency and amplitude as predicted (See Table 2.1). 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 2.10. The resulting regression equation is:

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

($r = 0.75$, $F(1,13) = 17.2, p < .001$), 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

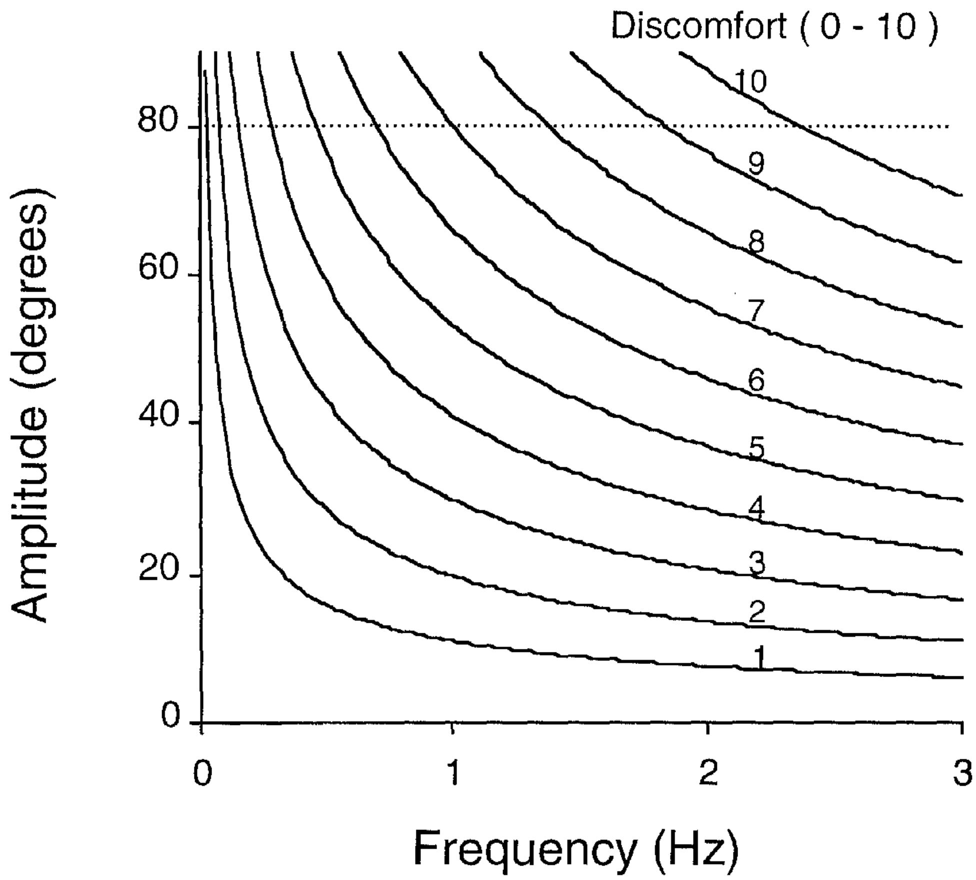

Figure 2.8. Equal discomfort strata based on solving regression equation for localized wrist flexion and discomfort. A flexion angle of 80° was considered the flexion range of motion limit for the wrist.

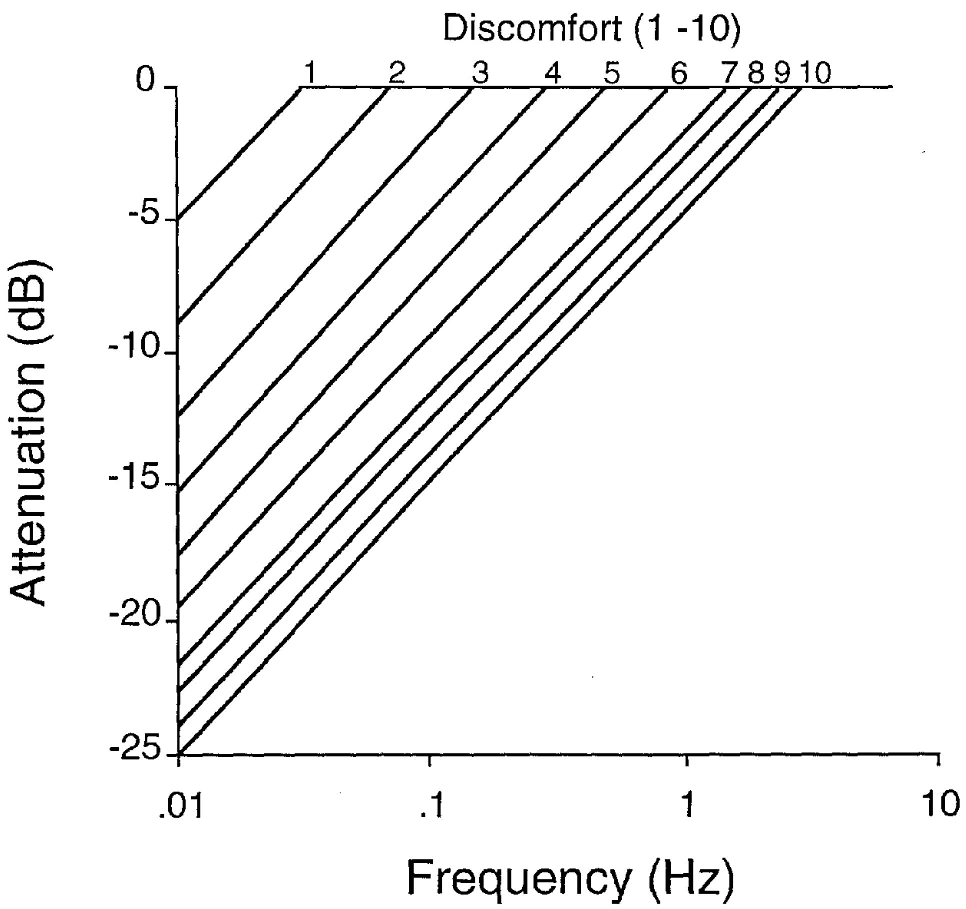

Figure 2.9: Frequency-weighted filters for discomfort levels 1 through 10.

was attributed to a carryover effect, however the outcome was unchanged when this case was included.

Table 2.1

Average RMS (Standard Deviation in Parentheses) Wrist Angular Motion for One-Hole Peg Task (4 Subjects)

	Experimental Condition			
Frequency	0.2 Hz		0.5 Hz	
Amplitude	20°	45°	20°	45°
	Average RMS Wrist Flexion			
Unfiltered	7.4° (1.0)	14.2° (2.3)	7.6° (0.5)	11.6° (1.6)
Filtered	3.4° (0.4)	5.5° (0.4)	4.6° (0.6)	7.0° (1.3)

2.4. 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 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 the high amplitude/ low frequency and the low amplitude/ high frequency conditions should result in equivalent filtered RMS levels. The outcome in Table 2.1 confirmed this. The unfiltered RMS flexion for the high amplitude/ low frequency condition was almost twice as great ($p < .05$) as the low amplitude/ high frequency condition (7° difference), but the filtered RMS levels for the same conditions were only

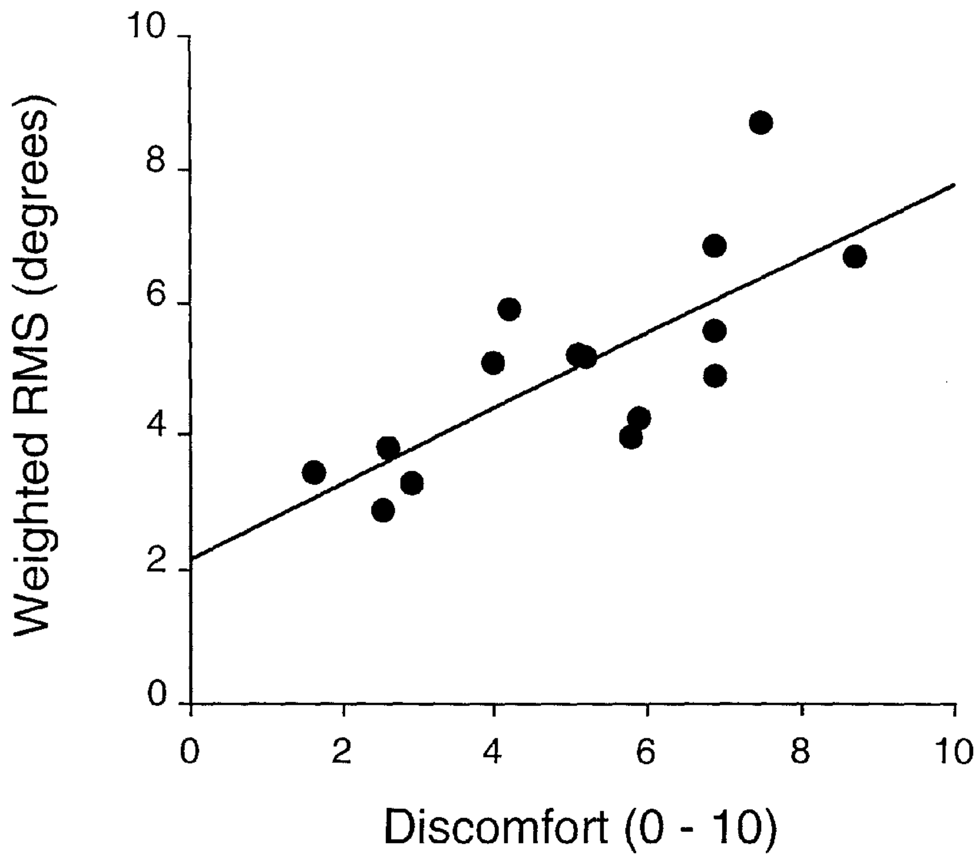

Figure 2.10: Filtered RMS for wrist flexion measured using an electrogoniometer regressed against localized discomfort ratings ($r = .75$) for four subjects performing a one-hole peg transfer task.

about one degree different ($p > .05$), which was within the measurement error of the electrogoniometer. Although the filtered RMS wrist flexion was proportional to reported localized discomfort levels (See Figure 2.10), 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 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. 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 Marras and Schoenmarklin's study. 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 that 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 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 analysts 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 physical stress likely affects different parts of the body differently, that approach seems 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 analyzed 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 of 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 2.8, and change the corresponding filter characteristics in Figure 2.9. 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 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 precisely known and should be the subject of future research.

3. A Single Metric for Quantifying Biomechanical Stress In Repetitive Motions and Exertions

3.1. Introduction

While high repetition, forceful exertions and awkward postures have been recognized as risk factors for cumulative trauma disorders (CTD) (Moore and Garg, 1994; Moore, et al., 1991; Aarås, et al., 1988; Tanaka, et al., 1988; Silverstein, et al., 1986; Armstrong, et al., 1982; Armstrong and Chaffin, 1979; Rothfleisch and Sherman, 1978; Hymovich and Lindholm, 1966), quantitative dose-response relationships between these risk factors and CTDs are still not available. This may be due to limitations associated with quantifying dose using multi-factor biomechanical measurements of force, posture and repetition.

In order to provide guidelines for task design and evaluation, investigators have turned to the psychophysical approach by using short-term responses to physical stress corresponding to controlled laboratory experiments. Previous research has suggested that the risk of injuries increase when task requirements exceed psychophysical acceptance (Herrin et al., 1986; Snook, 1985; Liles, et al., 1984; Snook, 1978; and Snook, et al., 1978). Results from psychophysical approaches have been supported by physiological measures (Öster, et al., 1994; Dahalan and Fernandez, 1993; and Kim and Fernandez, 1993). Psychophysical methods have been useful for evaluating tool designs (Schoenmarklin and Marras, 1989b; Örtengren, et al., 1991) and to examine specific upper extremity tasks for establishing work design guidelines (Krawczyk and Armstrong, 1991; Krawczyk, et al., 1992; Ulin, et al., 1992; and Snook, et al., 1995) .

Few studies have explored the combined effects of repetition, force and posture on the resulting psychophysical measures of subjective discomfort, or have attempted to model the combined relationship among them. Several investigation have investigated main effects but have not considered interactions. Krawczyk and Armstrong (1991) studied the effect of posture, force and repetition on perceived exertion using a Latin square design, thus interaction effects were not studied. Krawczyk, et al. (1992) also studied the effects of repetition and movement distance (posture) on perceived exertion using a visual analog scale, and on preferred weight (force) using the method of adjustment. Ulin, et al. (1993a) studied the effects of work location (posture) and repetition on perceived exertion for screw driving tasks. Ulin, et al. (1993b) also examined the effects of tool mass (force) and posture on perceived exertion for screw driving tasks. Snook, et al. (1994) investigated maximum acceptable forces for various paces, grips and types of motions, but since wrist flexion angle was fixed between 45° above and below the horizontal for all flexion and extension conditions, the angle effect was not included. Kim and Fernandez (1993) also used the method of adjustment to determine the maximum acceptable frequency for drilling tasks at different forces and wrist flexion angles (posture). Dahalan and Fernandez (1993) used the same approach to determine the maximum acceptable frequency (repetition) for gripping tasks at different force and duration. None of the studies mentioned above combined the effects of all three factors (force, posture and repetition).

Analytical methods are becoming available for quantifying direct biomechanical measurements in repetitive manual tasks. Spectral analysis was used as a method for quantifying repetitiveness and postural stress (Radwin and Lin, 1993). Radwin, et al. (1994) demonstrated the concept of using frequency weighted filters for processing continuous biomechanical measurements from repetitive motions in order to combine postural deviations and repetitive motions into a single quantity. The relative effect of wrist flexion angle and repetition on subjective discomfort determined the shape of these filters. Frequency weighted filters may be useful for exposure assessment instruments to assess repetitive motion stress (Radwin and Yen, 1993). Although frequency weighted filters show promise for quantifying repetitive and postural stress, the combination of repetition, posture and force has not yet been considered.

The objective of this study was to quantify and to model the relative effects of repetitive motion and force in order to investigate how biomechanical measurements of posture, force and repetition can be combined into a single metric corresponding to subjective discomfort. This study expanded the frequency weighted filter approach introduced in Radwin, et al. (1994) by adding a force factor. The relative effect of force, repetition and posture on subjective discomfort was used to demonstrate how force-posture frequency weighted filters can be established. It was hypothesized that there would be interactions among these factors. An experiment was also conducted to validate the resulting model using a simulated industrial task.

3.2. Methods and Results

3.2.1 *Experiment I: Model Development*

<u>Apparatus</u>

A fixture similar to the one used by Snook, et al. (1995) was used in this experiment for controlling wrist flexion range and hand force (see Figure 3.1). A Magnetic Power Systems, Inc. Model B-5 electric magnetic brake and a TC-5 torque controller were used for controlling resistance to motion. The input current to the brake was adjusted to control torque level. Torque resistance from the brake was calibrated by hanging a small container from the outer edge of a 15 cm diameter circular plate centered on the crank spindle. Lead beads were added by increments into the container until the weight provided enough torque to overcome the resistance from the brake for a given current. Since the weight of the container was always perpendicular to the moment arm (the radius of the circular plate), the product of the weight of the filled container and the radius of the plate determined the torque level. This calibration procedure was performed for eight different levels of current in a random order, and was replicated three times. Linear regression ($r^2 = 1.00$) was used for determining the required input current to provide the desired resistance.

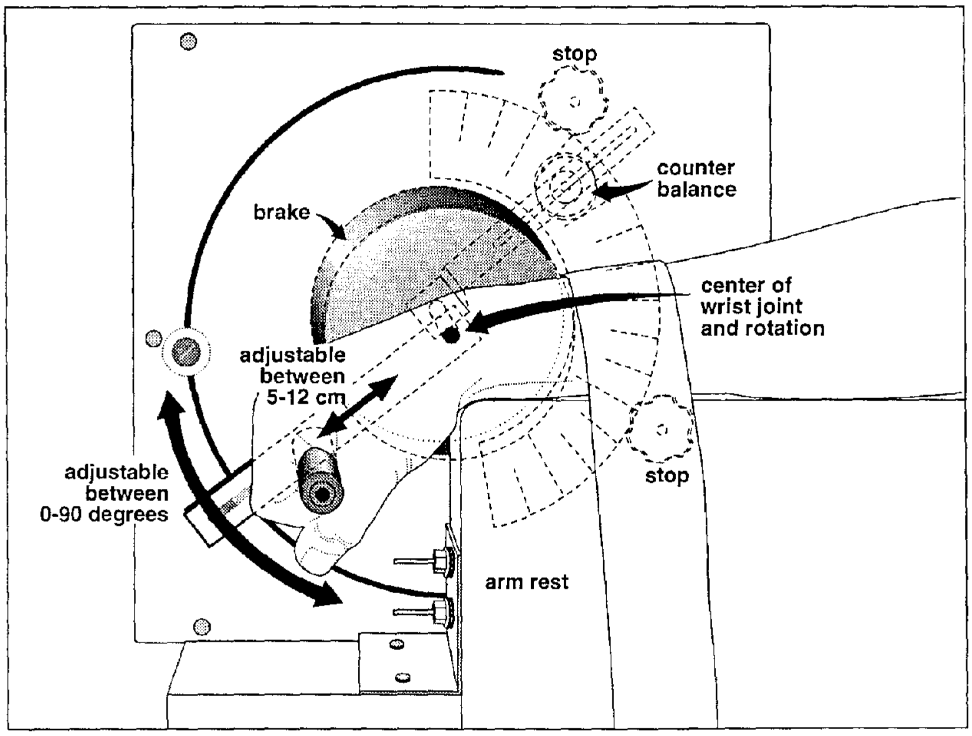

Figure 3.1. Fixture for controlling force and flexion angle.

A Plexiglas handle (2 cm diameter and 13 cm long) was attached perpendicularly to a bar fixed to the brake spindle (see Figure 3.1). The handle was adjusted so that the wrist joint center of rotation was aligned with the rotation center of the crank when grasping the handle. The distance between the center of grip and the wrist joint center of rotation for each subject was measured to determine the torque level in order to assure that every subject flexed against the same resistance for all experimental conditions with the same resistance. A moveable weight counterbalanced the load of the handle and bar. A clutch was installed at the brake spindle so subjects flexed against resistance from the brake to a pre-determined angle, but experienced nominal resistance (0.015 Nm) during extension. The fixture was located on top of a table that was adjusted so subjects sat in an upright position with the elbow at seated elbow height and the forearm and upper arm formed a right angle. An arm rest with a Velcro strap was used for providing stability and for controlling forearm posture to assure that the task was performed with the proper wrist motion. An adjustable mechanical stop was set for the resting posture at the horizontal position and another was adjusted to set the wrist flexion range.

The task was paced by two auditory cues and a visual display. The wrist flexed on one tone and extended on another tone. The period between the first tone and the second tone was set to one second for all conditions. Consequently the actual rest period varied, depending on the pace. The rest time remaining was indicated on a visual display. Subjects were instructed to relax in between exertions.

<u>Experimental Design and Procedure</u>

The experiment was a $2 \times 2 \times 2$ repeated measures full factorial design with pace, force, and wrist flexion angle as the independent variables. Subjective discomfort was the dependent variable. The experimental task involved repetitively flexing the pronated wrist from a neutral posture to a given angle against a controlled resistance while holding a handle in a power grip. Wrist flexion was controlled between a neutral posture and 15°

flexion or 45° flexion. Force was controlled at 15 N and 45 N by setting the brake at appropriate torque levels. The task was performed at 3 s/motion and 15 s/motion. Experimental conditions were presented to each subject in a random order. Only one experimental condition was presented to a subject on a given 24 hour period. Every condition was performed continuously for one hour. A two-minute warm-up period was provided at the beginning of each session.

Subjects were advised that symptoms of discomfort included aching, fatigue, soreness, warmth, cramping, pulling, numbness, tenderness, pressing or pain. They were required to be symptom-free at the beginning of every session. Discomfort was measured at the end of each session using a ten centimeter visual analog scale anchored as "No Discomfort" at 0 cm, and as "Very High Discomfort" at 10 cm. A thin 0.5 cm vertical line was placed on the scale to indicate the mid-point of the scale. Subjects drew a vertical line across the horizontal scale to indicate their discomfort level.

Multiple regression and a mixed model analysis of variance with subjects as a random effects blocking variable were used to analyze the discomfort data. The resulting regression model was then used to specify the attenuation slopes for frequency weighted filters (Lin, et al., 1994 and Radwin, et al., 1994).

Subjects

Seven subjects (six males and one female) ranging between 21 and 25 years were recruited from the university campus. All subjects were right handed and had no restriction of hand/arm motion or history of hand/arm injuries. None of the subjects had industrial work experience. Subjects were paid on an hourly basis for participation. One of the seven subjects dropped out from the experiment due to outside activities prior to the last two sessions. Data from these two sessions were treated as missing values and were estimated using the maximum likelihood method (BMDP Statistical Software, Inc.). The two estimated values were used in place of the two missing data in all analyses.

Results

Mean and standard deviation discomfort ratings for all eight conditions of pace, exertion, and angle are shown in Figure 3.2. Results from repeated measures analysis of variance revealed that pace (F (1, 6) = 19.45, $p < .05$), exertion (F (1, 6) = 45.94, $p < .05$), and angle (F (1, 6) = 13.47, $p < .05$) were all significant main effects. As the pace changed from 15 s/motion to 3 s/motion, average discomfort ratings increased from 2.83 (*s.d.* = 1.78) to 4.52 (*s.d.* = 2.13). The increase of force from 15 N to 45 N increased average discomfort ratings from 2.45 (*s.d.* = 1.44) to 4.90 (*s.d.* = 2.00). As the wrist flexion angle increased from 15° to 45°, average discomfort ratings increased from 3.10 (*s.d.* = 1.86) to 4.25 (*s.d.* = 2.25). No interaction effects between pace and exertion (F (1, 6) = 0.31, $p > .05$), between exertion and angle (F (1, 6) = 4.17, $p > .05$), between pace and angle (F (1, 6) = 0.14, $p > .05$), or among the three factors (F (1, 6) = 0.07, $p > .05$) were observed.

In order to determine the attenuation slope for a frequency weighted filter (Radwin, et al., 1994) , a linear regression model was used with mean discomfort as the dependent variable, and the logarithm of frequency, exertion and wrist flexion angle as the independent variables. The resulting regression model was:

$$D = 10^{(-0.18 + 0.51 \log E + 0.25 \log A + 0.27 \log F)} - 1$$

($r^2 = .98$, F (3, 4) = 51.10, $p < .01$), where D was discomfort (scale between 0 to 10), E was the exertion level (N), A was the wrist flexion angle (degrees), and F was frequency (Hz) which was the inverse of pace. Equal discomfort strata were determined by solving the regression equation.

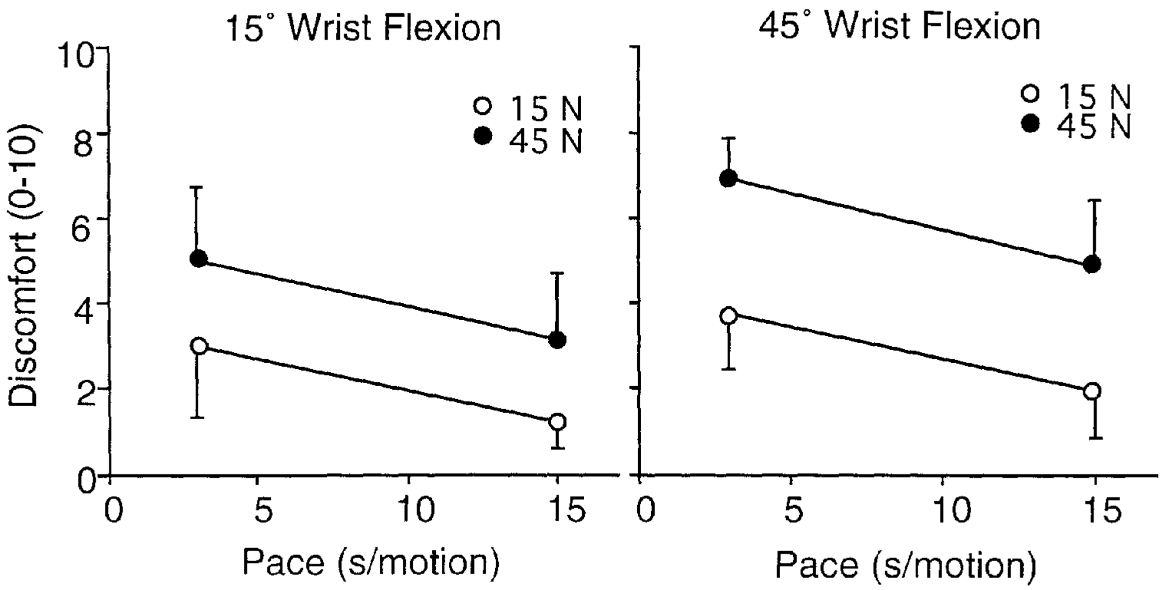

Figure 3.2. Mean and standard deviation of discomfort ratings for all conditions (7 subjects)

The strata for a discomfort level of four are shown in Figure 3.3 with exertion contours plotted against frequency and angle. Equal discomfort strata indicate corresponding exposures of exertion level, wrist angle and frequency that will result in equivalent levels of discomfort. For example, a task that requires 28 N exertion and 21° wrist flexion at the frequency of 0.2 Hz and a task that requires 30 N exertion and 39° wrist flexion at the frequency of 0.1 Hz would both result in a discomfort level of four.

<u>Force and Frequency Weighted Angle Filter</u>

When biomechanical measurements include force and posture, both factors contain the properties of magnitude and frequency. A frequency weighted angle filter would weigh flexion angle (degrees) by the corresponding frequency in proportion to the equal discomfort function. Combining posture and force would therefore require a three dimensional filter network that has the dimensions of force, posture and frequency. This study will assume force is a constant level. Consequently the wrist angular data are filtered through a frequency weighted angle filter and adjusted by the corresponding force effect. This concept is illustrated in Figure 3.4. This process enables continuous flexion angle data to be filtered and integrated, so it can be quantified as a single quantity.

The attenuation slope for a frequency weighted filter is expressed as decibels per decade, and can be obtained by algebraically solving the discomfort regression equation at any given discomfort and exertion level. The angular attenuation over one decade is:

$$\begin{aligned} A_{dB} &= 20 \times \log \left[\frac{A_{F/10}}{A_F} \right] \\ &= 20 \times \left[\log(A_{F/10}) - \log(A_F) \right] \end{aligned}$$

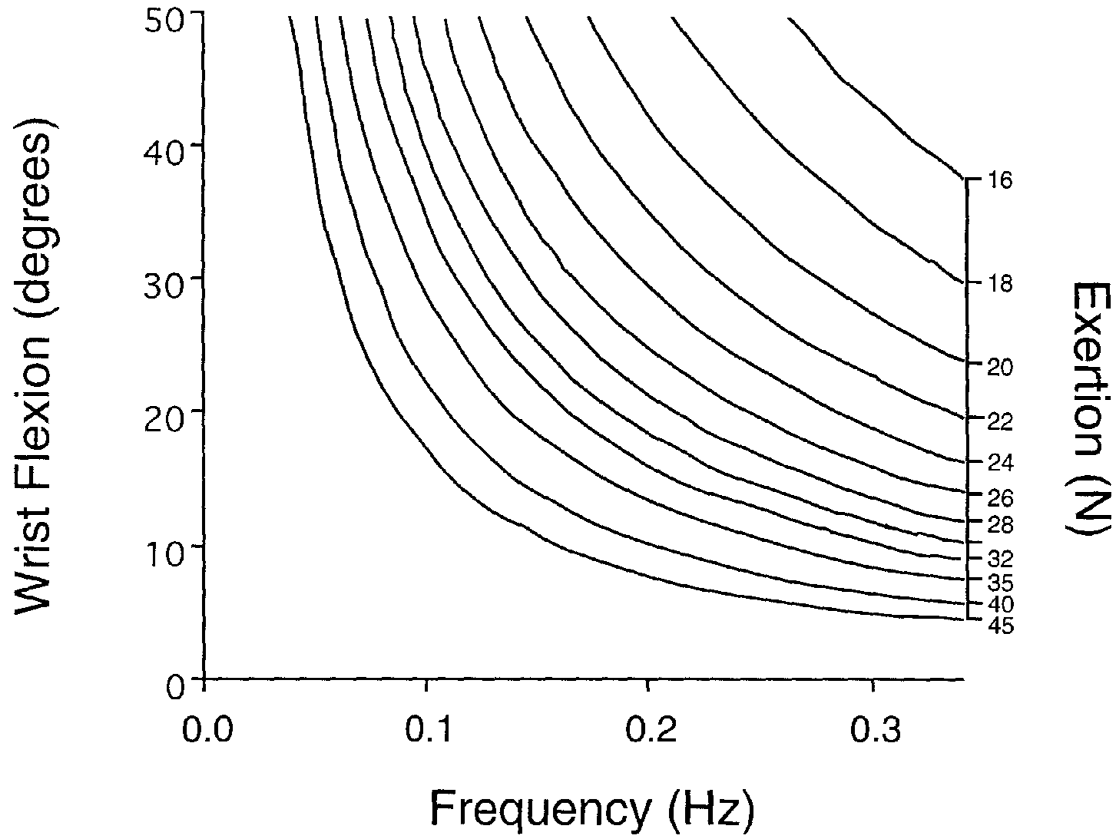

Figure 3.3. Equal discomfort strata for discomfort level four.

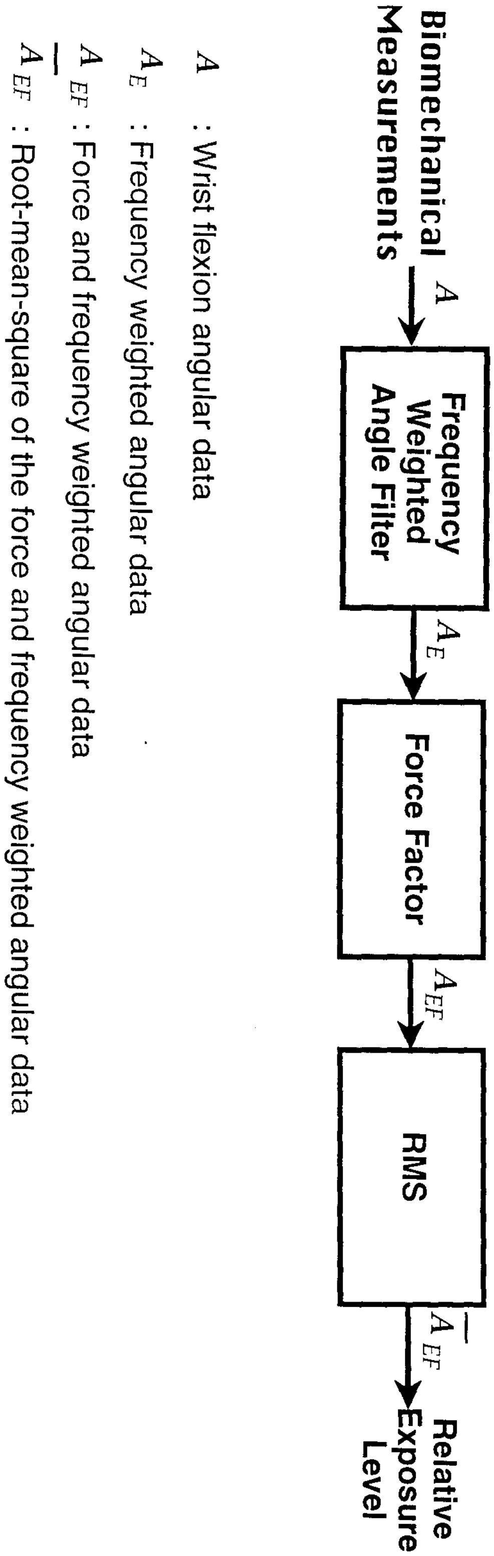

Figure 3.4. Flow chart for wrist flexion angular data processing and analyzing

where A_{dB} is the angular attenuation, A_F is the wrist flexion angle at frequency F and $A_{F/10}$ is the wrist flexion angle at a frequency one decade less than F for a given discomfort and exertion level. Based on the discomfort regression model the attenuation slope for the corresponding frequency weighted angle filter is:

$$\begin{aligned} A_{dB} &= 20 \times \left[\log(A_{F\,=\,0.06\,Hz}) - \log(A_{F\,=\,0.6\,Hz})\right] \\ &= 20 \times (2.24 - 1.14) \\ &= 22 \;\; dB\,/\,decade. \end{aligned}$$

The frequency weighted filter was modeled using MATLAB™ (The MathWorks, Inc.) as a finite impulse response (FIR) high-pass filter having a 22 dB/decade attenuation slope in the linear phase region, as suggested by the discomfort model (see Figure 3.5). Finite impulse response filters are nonrecursive filters that have outputs solely dependent on the present and past inputs. The primary advantages of FIR filters are that they can be designed to have linear phase and that they are inherently stable.

The equation for the FIR filter is:

$$y(nT) = \sum_{k=0}^{42} b_k\, x(nT - kT)$$

Coefficients of the difference equation are listed in Table 3.1, where $y(nT)$ is the output associated with the current sample time nT and $x(nT - kT)$ is the input value, k sample points in the past. The output value $y(nT)$ of the frequency weighted filter is the weighted sum of the input for the current sample time, $x(nT)$, and the input values of the preceding 42 sample points.

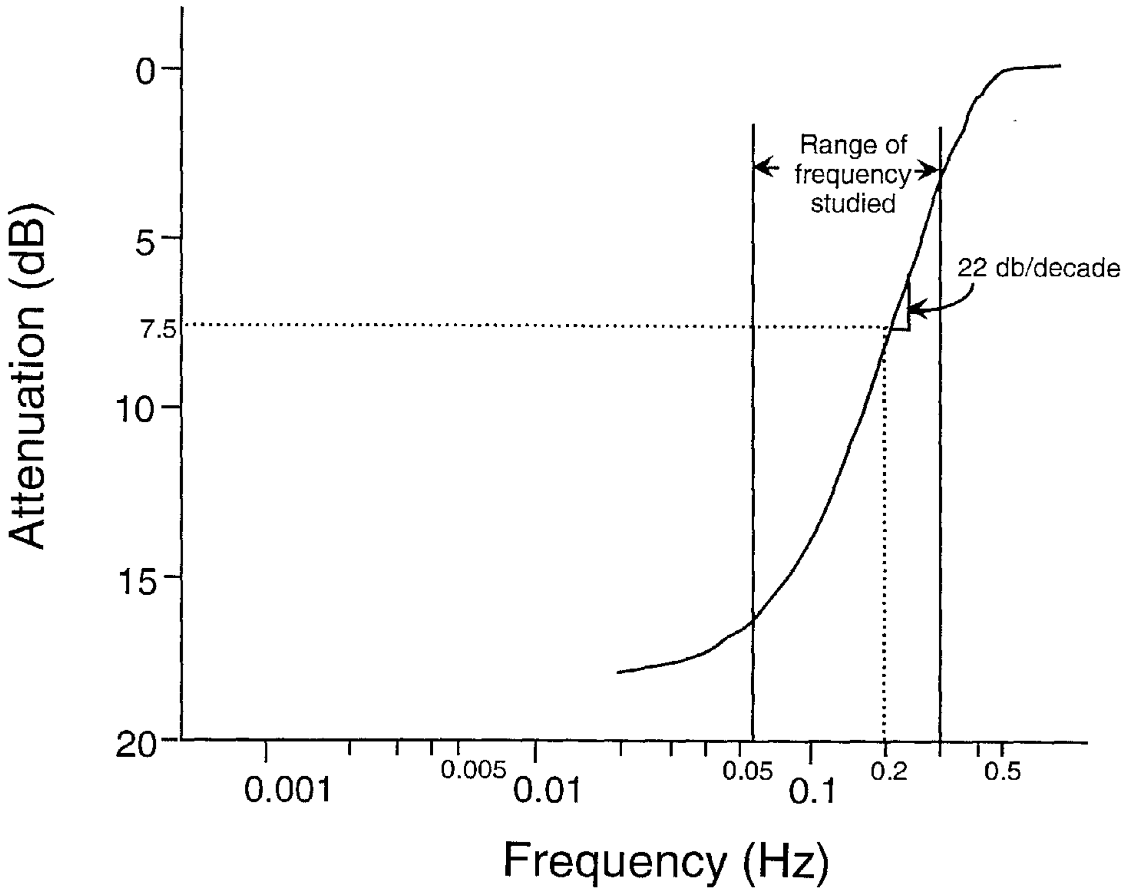

Figure 3.5. Characteristics of the frequency weighted angle filter

Table 3.1: Coefficients for the FIR Filter

k	b_k
0	0.0002
1	0.0000
2	-0.0003
3	-0.0007
4	-0.0014
5	-0.0024
6	-0.0038
7	-0.0057
8	-0.0081
9	-0.0110
10	-0.0145
11	-0.0183
12	-0.0224
13	-0.0268
14	-0.0312
15	-0.0355
16	-0.0395
17	-0.0430
18	-0.0460
19	-0.0482
20	-0.0496
21	0.9503
22	-0.0496
23	-0.0482
24	-0.0460
25	-0.0430
26	-0.0395
27	
28	-0.0312
29	-0.0268
30	-0.0224
31	-0.0183
32	-0.0145
33	-0.0110
34	-0.0081
35	-0.0057
36	-0.0038
37	-0.0024
38	-0.0014
39	-0.0007
40	-0.0003
41	0.0000
42	0.0002

The upper bound for the range of wrist flexion was set to 65 degrees in order to cover the range of dynamic wrist motion for more than 95 percent of the male population (Ojima, et al., 1992). This angle was then used as the reference level for calculating the angular attenuation (dB) at a given frequency and force level by algebraically solving the discomfort equation. A cut-off frequency of 0.5 Hz was determined by solving the discomfort equation so that at the 45 N exertion, the angular attenuation level at the cut-off frequency would be 0 dB. According to the discomfort model at the frequency level of 0.2 Hz, an exertion level of 45 N would result in 9 dB of angular attenuation and an exertion level of 15 N would result in 28.5 dB of angular attenuation. The attenuation level that resulted from the frequency weighted filter (see Figure 3.4) at the frequency level of 0.2 Hz was 7.5 dB. Therefore the difference in attenuation resulting from the discomfort model and from the frequency weighted filter was then adjusted by the corresponding proportion of the force factor. The force factor was 0.84 (-1.5 dB) for a 45 N exertion and was 0.09 (-21 dB) for a 15 N exertion. The output values $y(nT)$ from the frequency weighted filter were then multiplied by the force weighted factor to account for the force effect. The root-mean-square (RMS) of the force and frequency weighted angular data were then used to represent the relative exposure level (see Figure 4).

3.2.2. *Experiment II: Model Validation*

<u>Apparatus</u>

A special peg board was designed to control the resistance force during peg insertion (Figure 3.6). Jergens Corp. ball plungers were used to independently control the resistance when each peg inserted into a peg hole. The tighter the ball plunger was screwed, the higher the resistance. The resistance from each ball plunger was set by repeatedly adjusting each ball plunger and slowly pressing a strain gage load cell against a peg until the peak force reading from the oscilloscope was within ±2% of the desired resistance level. Since subjects needed to exert enough force to overcome the resistance to insert the pegs, the resistance settings were used for controlling the force conditions.

A horizontal bar was located in front of the peg board. The height of the horizontal bar was adjusted in order to control the wrist flexion angle.

Two 2 × 4 peg boards were placed adjacent to each other on an adjustable height table making a 2 row by 8 column matrix. The table was adjusted so that the peg board was at the seated elbow height. Subjects continuously received pegs from a chute located next to the seat on their dominant side. Subjects were instructed to insert pegs in a left to right fashion from the top row to the bottom, and to finish one peg board before inserting pegs into another. After a peg board was filled, the experimenter replaced it with an empty peg board, removed pegs from the filled peg board, and fed the pegs into the slot.

A Penny and Giles Biometrics model M110 strain gauge wrist electrogoniometer was fasted across the dorsal side of the wrist to continuously measure wrist flexion angle. The lateral epicondyle, radial styoid and second metacarpophalangeal joint were used as bony landmarks for aligning the wrist to determine the neutral posture (Schoenmarklin and Marras, 1989a). The electrogoniometer was calibrated by setting the zero degree at the neutral wrist flexion. A MacAdios 12-bit analog-digital converter, LabView® software (National Instruments Corp.) and a Macintosh II/fx microcomputer were used for sampling posture signals from the electrogoniometer and for implementing the digital filter for the posture data. Wrist flexion angular data were sampled at 20 Hz.

Experimental Design and Procedures

The experimental task involved repetitively transferring a peg across the horizontal bar and inserting it into a peg board against a controlled resistance. The experiment consisted of three experimental conditions: (1) 15° wrist flexion at the pace of 10 s/motion against a 15 N resistance, (2) 15° wrist flexion at the pace of 5 s/motion against a 45 N resistance, and (3) 45° wrist flexion at the pace of 4 s/motion against a 45 N resistance.

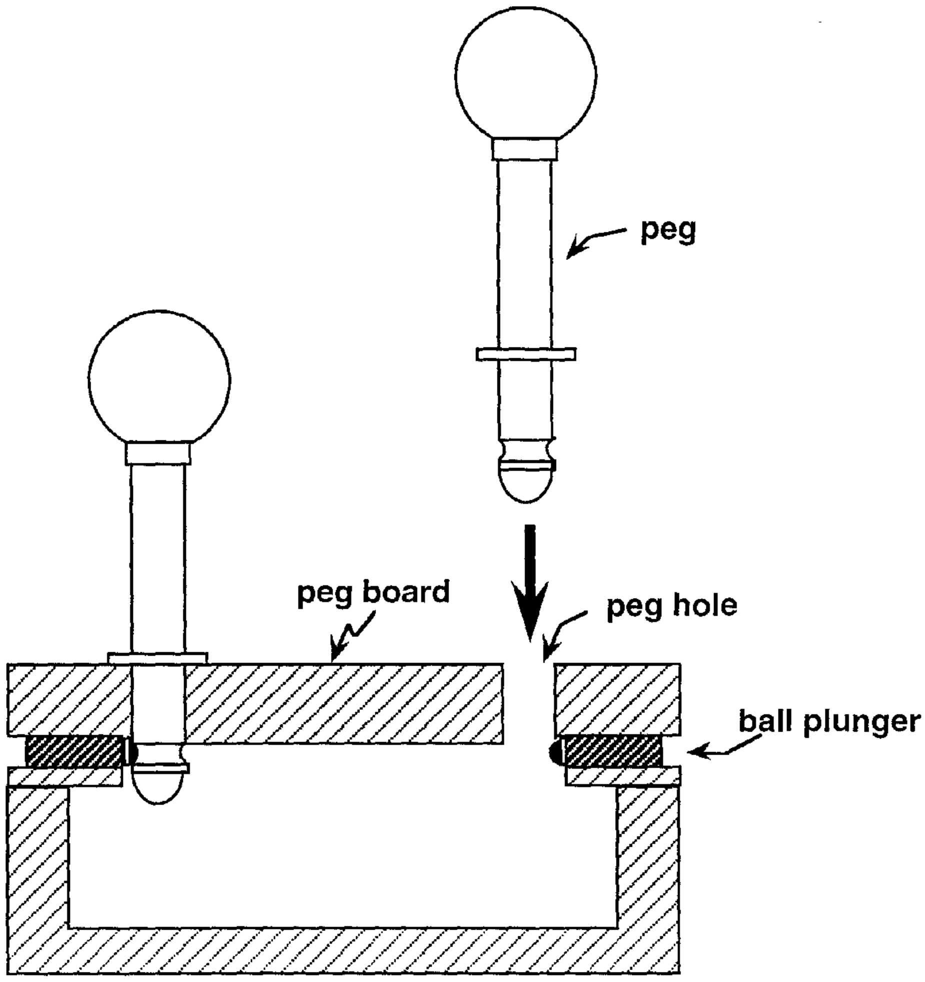

Figure 3.6. Side view of peg board with controlled resistance.

Experimental conditions were presented to each subject in a random order. Only one experimental condition was presented to a subject in a 24 hour period. Every condition was performed continuously for one hour. A two-minute warm-up period was provided at the beginning of each session.

Symptoms of discomfort were as defined in Experiment I. Subjects were required to be symptom-free at the beginning of every session. Discomfort was measured using the same visual analog scale. A linear regression analysis was used with subjective discomfort as the dependent variable and the relative exposure levels as the independent variable. A mixed model analysis of variance with subjects as a random effects blocking variable and the experimental condition as the fixed effect was also conducted.

Subjects

Six male subjects were recruited by broadcasting electronic mail announcements and posting signs on the university campus. Age ranged between 19 and 22 years. Five subjects were right handed and one was left handed. Subjects were required to have no restriction of hand/arm motion, or history of hand/arm injury. Subjects were paid on an hourly basis.

Results

Mean and standard deviation of the subjective discomfort ratings and the relative exposure levels for the three conditions is listed in Table 3.2. Results from repeated measures analysis of variance revealed that experiment conditions had significant effects on both the subjective discomfort ratings (F (2, 10) = 33.5, $p < .05$), and the relative exposure levels (F (2, 10) = 67.56, $p < .05$). Pearson correlation coefficients between subjective discomfort ratings and the predicted relative discomfort for individual subjects ranged between 0.917 to 0.999 (*mean* = 0.966, *s.d.* = 0.038). A linear regression model was fit across subjects with subjective discomfort rating as the dependent variable and the relative exposure levels as the independent variable. The resulting pooled subject model was:

$$D = 1.71 + 0.49 \times \hat{D}$$

(r = .73, $F(1, 16) = 18.60, p < .01$), where D was discomfort (scale of 0 to 10), $\hat{D}$ was the relative exposure levels estimated by the RMS of the frequency and force weighted angular data.

Table 3.2: Mean and standard deviation for subjective discomfort ratings and the predicted relative discomfort levels (N=6 subjects)

Experimental Conditions			Subjective Discomfort Rating	Relative Exposure Level
Force(N)	Angle(°)	Pace(s/motion)	Mean (*s.d.*)	Mean (*s.d.*)
15	15	10	1.70 (1.75)	0.92 (0.84)
45	15	5	4.65 (1.35)	5.83 (1.67)
45	45	2	6.38 (0.92)	8.82 (1.28)

Validation of the Discomfort Model Using Data from Snook, et al. (1995)

Snook, et al. (1995) used the method of adjustment to estimate the maximum acceptable force for wrist flexion at various levels of repetition. Subjects worked seven hours daily in their study and were instructed to work as hard as they could without developing "unusual discomfort" by selecting the maximum acceptable force. Snook, et al. (1995) summarized the estimated maximum acceptable forces for wrist flexion between 45° above and below the horizontal at 2 motions/min (0.03 Hz), 5 motions/min (0.08 Hz), 10 motions/min (0.17 Hz), 15 motions/min (0.25 Hz), and 20 motions/min (0.33 Hz) by different percentages of the female population studied. Data from table 12 in Snook, et al. (1995) was fit into the resulting discomfort model from the current study by (1) treating maximum acceptable forces as exertion levels, (2) assuming 90° wrist flexion for all conditions, and (3) converting paces into frequencies. Since the maximum acceptable force at 0.25 Hz for 90% of the female population was 12 N, the expected discomfort level is:

$$10^{(-0.18+0.51\log(12)+0.25\log(90)+0.27\log(0.25))} - 1 = 3.94.$$

The expected discomfort levels for the frequencies Snook et al. (1995) studied are summarized in Table 3.3. The resulting expected discomfort levels using Snook, et al. (1995) data should be equivalent if the current study model corresponds. Equivalent expected discomfort levels were observed among conditions between 0.17 Hz and 0.33 Hz. Differences among the expected discomfort levels between 0.17 Hz and 0.33 Hz were within 0.5 units (on a 10.0 point scale) with a coefficient of variation less than 0.03 for any given percentage of the female population. The mean expected discomfort levels from these conditions could be considered the maximum acceptable discomfort levels. The resulting maximum acceptable discomfort was 3.72 (*s.d.* = 0.10) for 90% of the female population for frequencies between 0.17 Hz and 0.33 Hz. When comparing expected discomfort levels from conditions of 0.03 Hz and 0.08 Hz, larger differences were observed (see Table 3.3).

Table 3.3: Expected discomfort levels from fitting data from Snook, et al. (1995) into the discomfort model from the current study (assuming 90° wrist flexion for all conditions)

	Pace of Motion				
Percent of Population	2 /minute (0.03 Hz)	5 /minute (0.08 Hz)	10 /minute (0.17 Hz)	15 /minute (0.25 Hz)	20 /minute (0.33 Hz)
90	2.11	3.98	4.57	4.80	4.78
75	2.90	4.99	5.71	6.00	5.97
50	3.61	5.90	6.74	7.11	7.08
25	4.24	6.70	7.65	8.09	8.04
10	4.74	7.35	8.39	8.86	8.81

3.3. Discussion

Results of this study showed that the main effects of frequency, force and angle were all significant, and that no significant interaction effects among them were observed. A linear model therefore can be used to describe to relationship among the three factors and their effects on subjective discomfort. These findings are supported by other studies. Dahalan and Fernandez (1993) found that grip force was a significant main effect on maximum acceptable frequency and ratings of perceived exertion in simulated gripping task. Marley and Fernandez (1995) found that maximum acceptable frequency decreased as wrist deviation increased. Snook, et al. (1995) observed that maximum acceptable force levels decreased as repetition increased. Kim and Fernandez (1993) indicated that both force and wrist flexion angle (posture) were significant main effects for maximum acceptable frequency and ratings of perceived exertion for drilling tasks. They also failed to find a significant interaction between force and wrist flexion angle as indicated in this study. Ulin, et al. (1993a) found that work location (posture) and work pace (frequency) were both significant main effects on ratings of perceived exertion, and that the interaction effect was not significant. Results from Ulin, et al. (1993b) revealed that tool mass (force) and work location (posture) were both significant effects in determining ratings of perceived exertion in screw driving tasks, and the interaction effect was not significant. Krawczyk, et al. (1992) found that frequency was a significant main effect for both preferred weight and perceived exertion, and distance (posture) was a significant effect for preferred load. The interaction effect of frequency and distance (posture) was not significant for both preferred load and perceived exertion. Although an additive model was apt for subjective discomfort, it is not yet clear if a linear model will suffice for morbidity data (Silverstein, et al., 1986).

Studies have indicated that the psychophysical approaches can be used to define 'acceptable' exposure levels (Snook, et al, 1995 and Marley and Fernandez, 1995).

Discomfort models, like the one developed in the current study, may be used for comparing task designs for various combinations of force, posture and frequency. Consequently they are more efficient in providing guidance for task design and evaluation than information solely from the method of adjustment unless many different combinations of force, posture and frequency are included. The current research suggests that use of the method of adjustment such as the one used by Snook, et al (1995) for determining acceptability, combined with continuous discomfort models, such as the one established in this study, together can be used to establish the maximum acceptable discomfort levels which are critical for task design and evaluation, since requirements exceeding these levels would result in unusual discomfort.

The maximum acceptable force data from Snook, et al. (1995) were fit into the current discomfort equation to validate the model under two assumptions. The first assumption was that the additive relationship among force, repetition and wrist flexion angle for the one hour exposure in the current study corresponds to the seven-hour exposure for the range of wrist flexion examined (45° above and below the horizontal). The second assumption was that subjects maintained a fixed reference in determining the maximum acceptable force, so that the selected maximum acceptable forces would result in approximately the same level of discomfort across different repetition rates. Under these two assumptions, the discomfort model could be validated by comparing expected discomfort levels across different combinations of maximum acceptable forces and repetition rates. Equivalent discomfort levels occurred for conditions between 0.17 Hz to 0.33 Hz.

A discrepancy occurred between 0.03 Hz and 0.08 Hz when the expected discomfort levels for these two conditions deviated from the equivalent expected discomfort levels (see table 3). An explanation for this discrepancy may be strength limitations. Hallbeck (1994) showed that mean flexion strength for the female population was 48.28 N at 45° wrist extension and was 59.76 N at 45° wrist flexion . The maximum acceptable force observed in Snook et al. (1995) for wrist flexion for 50% of the female population at 0.08 Hz was 32.3 N which was more than 66% of the mean flexion strength at 45° wrist extension and more than 50% of the mean flexion strength at 45° wrist flexion observed by Hallbeck (1994). It is possible that during excessive exertions, force itself would be enough to cause unacceptable discomfort without regard for repetition (i.e. slower paces may not accommodate for excessive force). The fact that the maximum acceptable forces for 0.08 Hz and 0.03 Hz (Snook, et al., 1995) were the same further supports the explanation that the maximum acceptable force may have been limited by strength rather than repetition. This finding also indicated that excessive force requirements, even when performed at a relatively low pace, may result in greater discomfort than anticipated by the discomfort model. Task requirements exceeding these forces thus should be avoided regardless of the resulting discomfort levels predicted. Considering limitations from the speed and the range of wrist motion based on the same reasoning, it further suggests that the discomfort model might deviate from linearity when task requirements reach certain extremes of physical exposure, i.e. these extremes of exposures define the boundaries for applications of the linear discomfort model. Future investigations should be conducted to determine these extremes and to investigate how other task parameters may contribute to these limits (e.g. since wrist posture has significant effect on strength, the strength limit will vary for tasks with different ranges of wrist motion.).

Radwin, et al. (1994) studied the relative effects of frequency and wrist flexion angle on subjective discomfort and suggested that while other control variables were set at the same level, discomfort ratings for a task performed at the 0.1 Hz and 0.05 Hz were not significantly different. This finding suggests that sufficient recovery may occur for tasks performed at a pace slower than a certain frequency, where discomfort may become insignificant. Future studies should investigate discomfort from repetitive motion and exertion tasks when sufficient recovery occurs.

Based on data from Snook, et al. (1995) and the discomfort model in this study, and assuming 90° wrist flexion for all conditions, the maximum acceptable discomfort level for repetitive hand intensive tasks for 90% of the female population was 3.72. Figure 3.3 shows the equal discomfort strata for discomfort level four with exertion contours plotted against frequency and angle. Any combination of frequency and wrist flexion angle above the 28 N contour for tasks requiring 28 N or higher exertions would result in unacceptable discomfort. For instance, when a task requires 28 N exertions and 28° of wrist flexion, the frequency of the task would be unacceptable above 0.15 Hz. On the other hand, if a task needs to be perform at a frequency of 0.15 Hz with 28° of wrist flexion, exertions exceeding 28 N would not be acceptable for 90% of female population.

Although general applications of this research is premature, this study explored the relative effects among the three risk factors on discomfort and took the preliminary step in modeling the quantitative stress-strain relationship between the risk factors and subjective discomfort. Results from the validation experiment (Experiment II) showed that the discomfort model established in Experiment I had significant capability in predicting the subjective discomfort from a repetitive hand intensive industrial task, even though Experiment I was a highly controlled experiment that isolated the wrist motion while the validation experiment had minimal restrictions on motions of the upper extremity. The strong correlation between subjective discomfort ratings and the relative exposure levels estimate by the RMS of the force and frequency weighted angular data demonstrated the feasibility of implementing the force and frequency weighted angle filters in biomechanical exposure assessment instrumentation.

The shortcomings of the discomfort model included (1) the study only investigated wrist flexion motion with a power grip from the neutral position, which may not be representative for tasks involving different wrist motions (e.g. ulnar and radial deviations and wrist rotations) and different grip postures (e.g. pinch grip), (2) sustained postures and exertions were not included, (3) there were only two control levels within each factor, and (4) the boundaries for applications for the linear discomfort model were not defined. Future studies involving longer exposure and more levels of control, including the sustained level for each risk factor, are recommended for refining the discomfort model and for defining its boundaries.

This research investigated the short-term effects of repetitive motions and exertions. Subjective discomfort was selected as a short-term response to physical stress in this study. Discomfort is significant since discomfort in the work place may be associated with risk of injuries (Valencia, 1986) and should be reduced. Discomfort was considered also because it can be measured within a reasonable amount of time and discomfort can provide guidance in work design and evaluation, particularly when the quantitative exposure criteria for reducing the risk of CTDs is still unavailable. When such data becomes available, morbidity data could be used as the response for establishing frequency weighted filters in a similar manner.

4. Field Studies Using Spectral Analysis for Quantifying Upper Extremity Repetitive Motion

4.1. Introduction

Spectral analysis was demonstrated useful for quantifying continuous upper extremity motion associated with repetitive manual activities measured from electrogoniometers (Radwin, et al., 1994; Radwin and Lin, 1993; Radwin and Yen, 1993). The method was used for assessing repetitive wrist motion and postural stress in the laboratory using simple, highly controlled, peg transfer tasks. Spectra components were related to repetitive wrist motion at different frequencies; spectrum magnitudes were proportional to wrist movement size, and DC components indicated sustained postures. The current study investigates practical applications using that analytical method for assessing repetitive motion stress in the field.

4.2. Construction Operation

A construction wheel loader job will serve as the first example. Repetitive earth moving tasks are a concern because they are considered particularly fatiguing. Operator movements associated with two different construction vehicle cab designs were measured and compared. One vehicle had a conventional steering wheel and transmission lever for forward/ reverse and gear shifting. The alternate vehicle had a laterally tilting control stick for steering, and finger triggers for forward/ reverse and for gear shifting. A study was conducted for comparing operator movements between the two vehicles for the earth moving task. Electrogoniometers continuously measured upper extremity movements, and spectral analysis was used for quantifying motion for specific upper extremity joints associated with each cab.

Two Caterpillar Model 988 wheel loaders were used for this study. The vehicles were identical in every aspect except for the cab controls. Three experienced male drivers operated each vehicle while performing the earth moving task. The order vehicles were used was counterbalanced among operators. Operators repeatedly transferred soil from one pile to another, requiring the vehicle to back and turn 90° in order to accomplish the task. The task involved continuous steering and transmission shifts. When a pile was depleted, the soil was transferred back from the full pile to the depleted one. This load/ dump task was performed for 30 minutes and electrogoniometer data was continuously recorded.

An Exos wrist electrogoniometer measured wrist flexion/ extension and ulnar/ radial deviation of the hand operating the stick control. Penny and Giles strain gage electrogoniometers measured forearm rotation, elbow flexion/ extension, shoulder adduction/ abduction, and shoulder flexion/ extension. All electrogoniometers were independently calibrated within the range of motion representative of the task. Analog outputs from all measurement instruments were connected to an isolation/ booster amplifier and routed to a nearby van via a constant tension tether cable system. Analog data was sampled at 60 Hz and synchronized with a video image of the task (3). An interactive multimedia computer system was used for extracting biomechanical data associated with repetitive tasks for specific work elements using a computer-controlled VCR. Spectral analysis was used to characterize repetitive motion and postural stress. Repeated measures ANOVA was used for comparing the data associated with the two cabs.

A representative spectra for elbow flexion/ extension when using the conventional steering wheel and the stick steering control are shown in Figure 4.1. Mean joint RMS motion, repetition frequency, and sustained posture for six upper extremity joints are provided in Table 4.1. Neutral posture is 0° except for shoulder adduction/ abduction

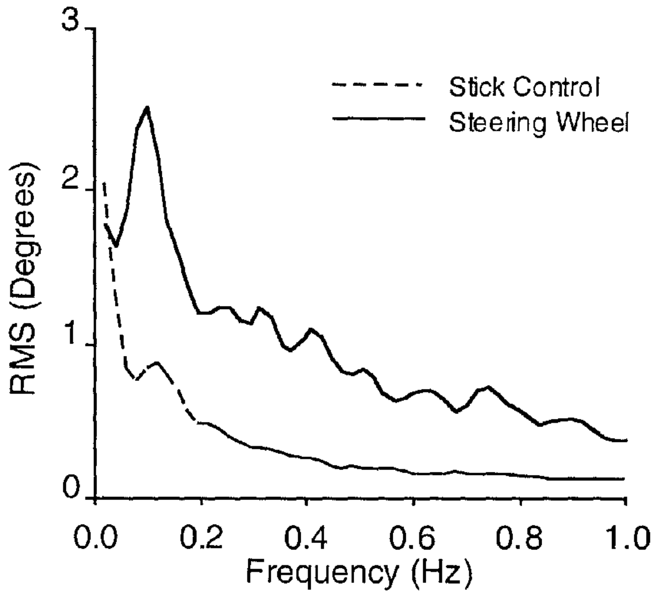

Figure 4.1. Spectrum for Elbow flexion/ extension using the stick and conventional steering controls.

which is 90°. Spectra for the steering wheel contained greater magnitudes and frequencies than for the stick control.

No significant difference ($p > .05$) in mean cycle time was observed between the stick control and steering wheel; mean cycle time was 15.7 s (SD=2.9) for the steering wheel and 15.9 (SD=3.5) for the stick. Wrist flexion/ extension frequency was 40 % greater for the wheel than for the stick (see Table 4.1). Elbow RMS flexion was 150% less, and repetition frequency was 57% less for the stick than for the steering wheel (see Table 1). Although RMS forearm rotation was 100 % less for the stick control, repetition frequency increased 37% (see Table 1).

Table 4.1

Mean and Standard Deviation of RMS Joint Motion, Sustained Posture and Repetitiveness Measured for Dump/ Load Task (3 Drivers).

		Wrist		**Shoulder**		**Forearm**	**Elbow**
	Control	**Rad/Ulnar**	**Flex/Ext**	**Add/Abd**	**Flex/Ext**	**Rotation**	**Flex/Ext**
RMS Motion (deg)	Wheel	5 (2)	6 (4)	4 (1)	10 (1)	22 * (12)	10 * (3)
	Stick	6 (5)	5 (1)	4 (0)	1 (1)	11 * (4)	4 * (1)
Sustained Angle (deg)	Wheel	-15 (2)	-27 (8)	38 (16)	44 (27)	-72 (8)	38 (24)
	Stick	-24 (1)	-11 (22)	51 (8)	25 (23)	-30 (23)	63 (5)
Frequency (Hz)	Wheel	0.134 (0.025)	0.125 * (0.006)	0.163 (0.034)	0.156 (0.037)	0.063 * (0.019)	0.109* (0.026)
	Stick	0.086 (0.006)	0.075 * (0.027)	0.105 (0.034)	1.023 (0.722)	0.100 * (0.020)	0.065 * (0.011)

* $p \leq .05$

4.3. Assembly Operation

A parts hanging job in a hardware assembly plant was studied because this work was considered highly repetitive, and serves as a second example. The job required seated operators to grasp small metal parts from a tray and position them onto a series of metal hooks that pass in front. The parts were transported on the hooks to a paint booth. The elements involved in this operations included:

- Gather Parts: Operator slides stock along tray
- Move Part to Hook: Operator places part on hook
- Idle: Operator rests between jobs

Penny and Giles electrogoniometers were attached to the operator's wrist for continuously measuring wrist flexion/ extension and ulnar/ radial deviation. A representative time series of wrist flexion/ extension is shown in Figure 4.2.

Examination of 80 series of wrist flexion/ extension data extracted and plotted separately for each cycle of the task reveals that if the measurements could not be averaged in the time domain (See Figure 4.3). However, when the posture data is transformed to the frequency domain, power spectra may be averaged since the phase information contained in the time domain is lost (See Figure 4.3).

The data was again broken down into elements, similar to above, however the Move Part to Hook element was further broken into three separate elements for low, medium, and high hooks. The three resulting spectra are presented in Figure 4.4. The magnitude and of the high hook spectrum was greater than the other two, and the peak frequency for the high hook was less than for the other two hooks.

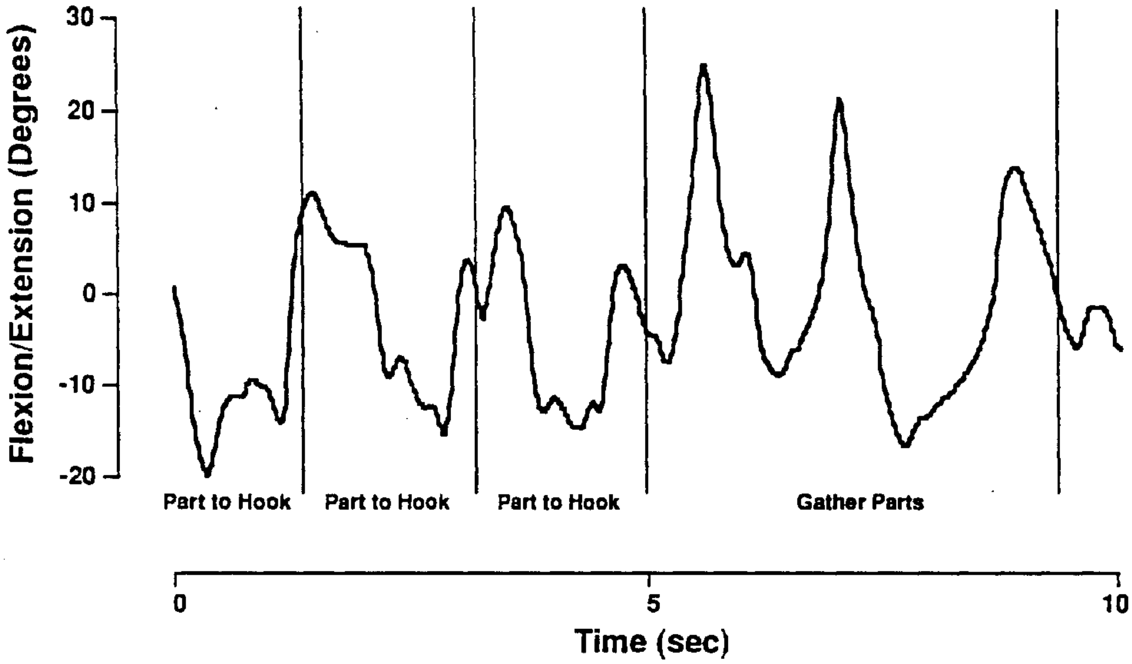

Figure 4.2: Representative wrist flexion/ extension time series for parts hanging operation.

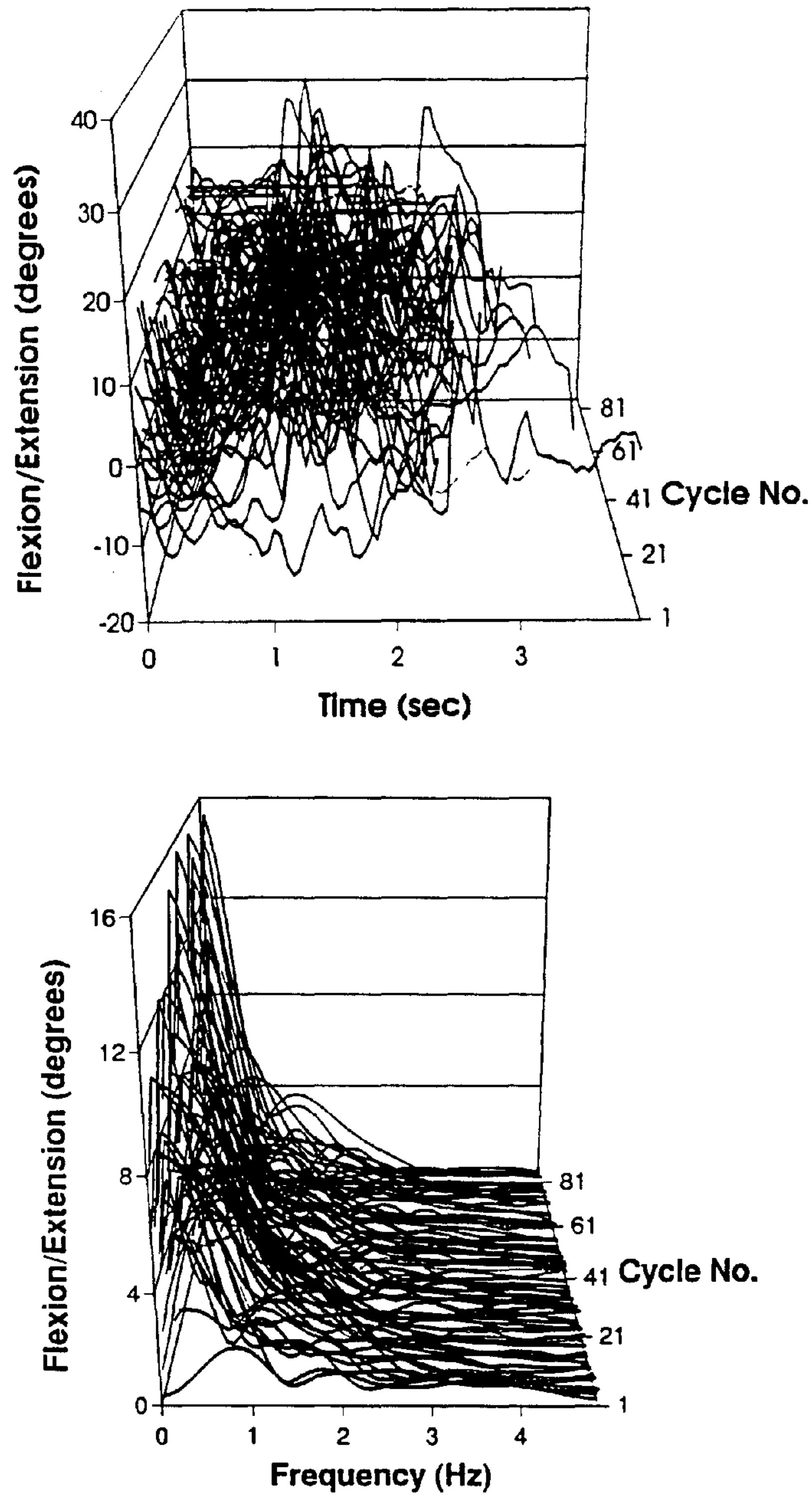

Figure 4.3: Upper plot shows flexion/ extension time series for individual cycles of parts hanging task. Lower plot shows how the same data transformed into the frequency domain lines up for averaging.

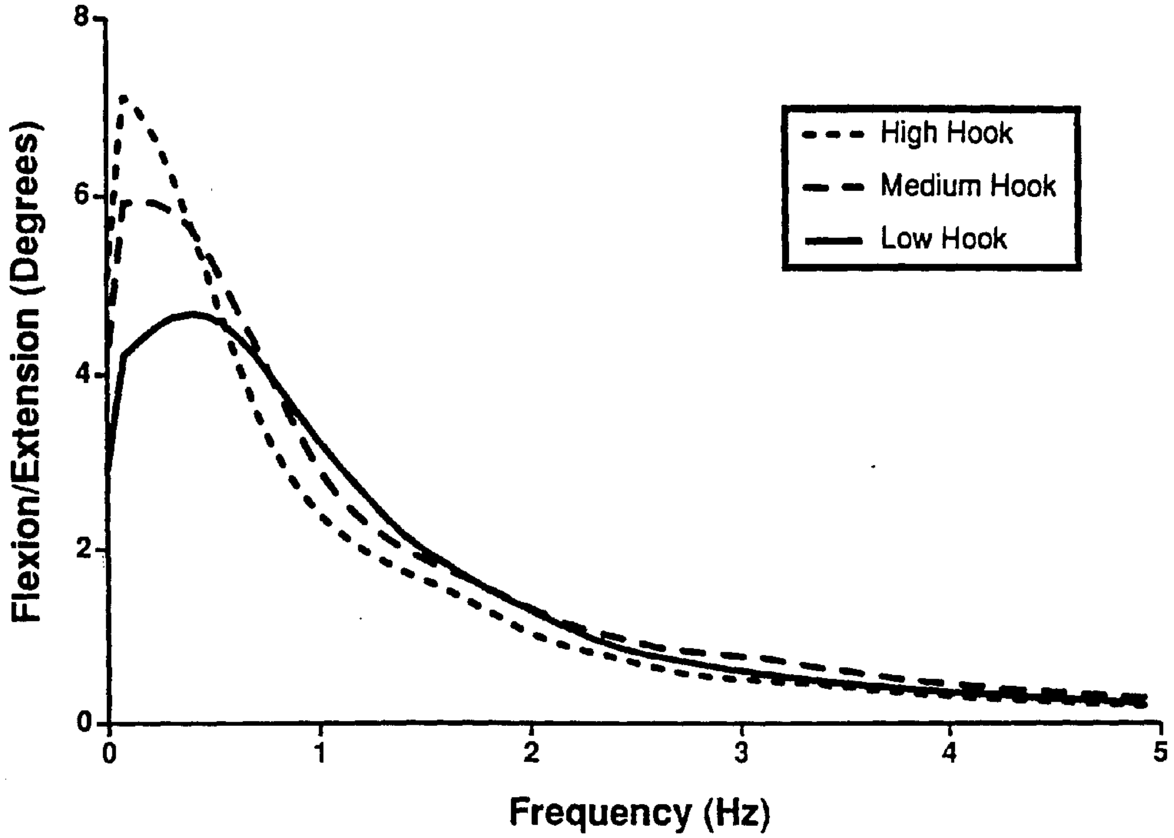

Figure 4.4: Spectra for parts hanging task averaged separately for high hooks medium hooks and low height hooks.

4.4. Discussion

It was hypothesized that the stick cab control would result in less upper extremity movements while providing similar work performance. Spectral analysis clearly quantified differences between the two job designs with respect to postural activity, repetitiveness, and sustained postures. The results demonstrate that specific aspects of physical stress exposure from repetitive movements can be quantified, and improvements in job design for a specific task can be objectively measured and analytically determined.

Similar results were obtained for the parts hanging operation, as was observed in the laboratory using peg boards. Spectral analysis was useful in distinguishing differences in postural stress and repetitiveness between the high hook and low hook elements. This information will be useful in prioritizing ergonomic interventions, balancing work among operators, and for balancing work rotation schedules.

Suitable data reduction techniques are needed for evaluating work methods, job designs, and for conducting large scale detailed epidemiological investigations of cumulative trauma disorder risk factors. Analytical methods that are capable of quantifying differences between specific job designs are needed for assessing improvements provided by specific ergonomic interventions. Methods such as spectral analysis will allow investigators to study operator exposure over longer periods and provide more accurate and precise data using continuous biomechanical measurements.

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List of Publications and Possible Future Publications Resulting from this Research

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