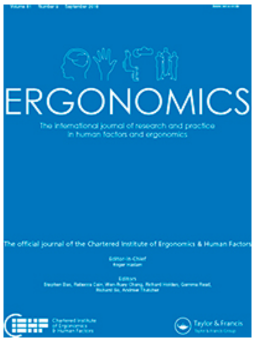

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Rapid Communication

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

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Keywords: Cumulative trauma disorders; Electrogoniometer; Hand; Kinematics; Repetitive trauma; Wrist.

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. 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.

1. Introduction

Upper extremity cumulative trauma disorders (CTD) are associated with repeated movements of the body and sustained postures (Hymovich and Lindholm 1966, Jensen *et al.* 1983, Silverstein *et al.* 1986, and many others). Extreme joint angles are also widely recognized CTD risk factors (Younghusband and 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, 1982, Keyserling 1986), they are extremely limited in their ability to characterize these stresses fully. 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 measure repetitive hand motion in manual tasks continuously. Although these instruments can measure movements more accurately and precisely 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 often 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, compromise 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 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.

2. Methods

Dependent variables in this study included wrist flexion/extension and ulnar/radial deviation angles. A Penny and Giles Biometrics model M110 strain gauge 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). 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).

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 3 min rest period was provided between every set. Two learning sets were performed prior to collecting data.

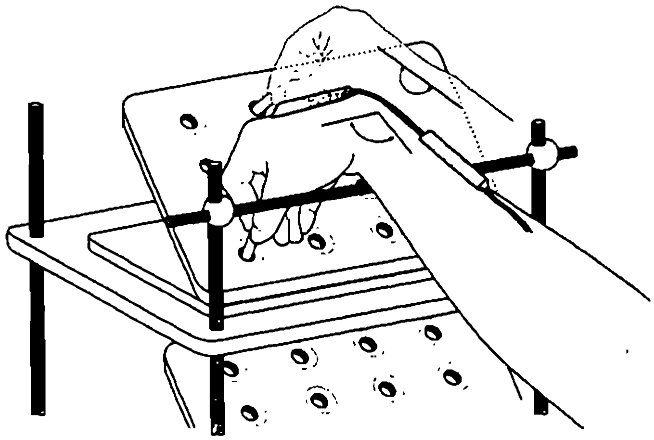

Figure 1. Experimental apparatus including two 4 × 4 peg boards located on two adjustable height shelves. The inclination angles were also adjustable and a bar was located in front of the upper peg board for controlling wrist flexion angle. Flexion angle increased when grasping pegs from Row 1 to Row 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 *fundmental 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 elments. 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 $N \geq L$, and padded with zeros. This process is described by the following expression:

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

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

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

3. Results and discussion

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 did not have an obstruction and its angluar 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 $\Delta f = 0{\cdot}086$ 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 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 ($F(1,8) = 15{\cdot}07$, $p < 0{\cdot}01$) 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).

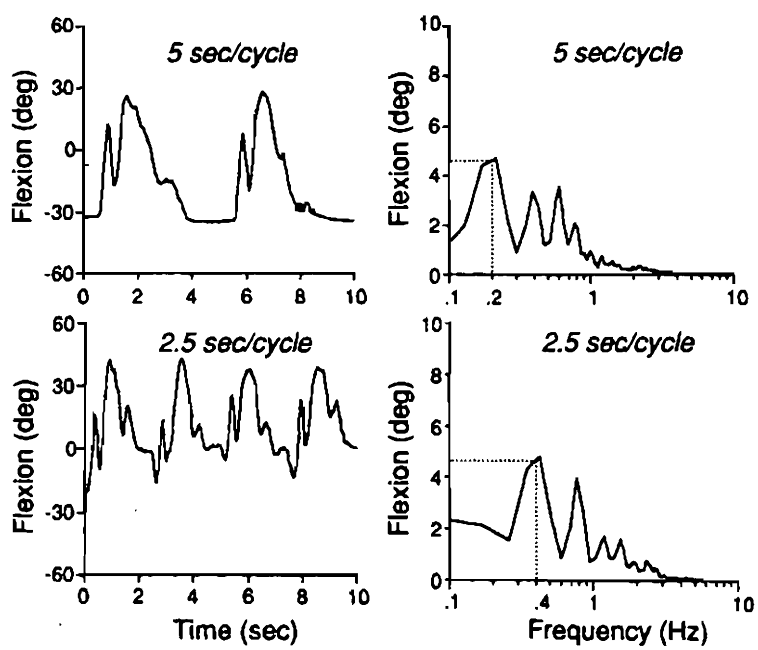

Figure 2. Representative time series and spectra for transferring pegs at two paces (1 subject). The fundamental frequency and its associated harmonics doubled from 0·2 Hz to 0·4 Hz as pace increased from 5 s/cycle to 2·5 s/cycle.

The power spectrum fundamental frequency magnitude, averaged over two paces and stratified by row for five subjects, is plotted in figure 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 ($F(3,12)=30{\cdot}6$, $p<0{\cdot}001$). This effect was also significant ($p<0{\cdot}001$) 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 ($p<0{\cdot}05$), except for the difference between Row 1 and Row 2. No significant ($p<0{\cdot}1$) magnitude effects were observed for pace. or for the interaction between pace and row.

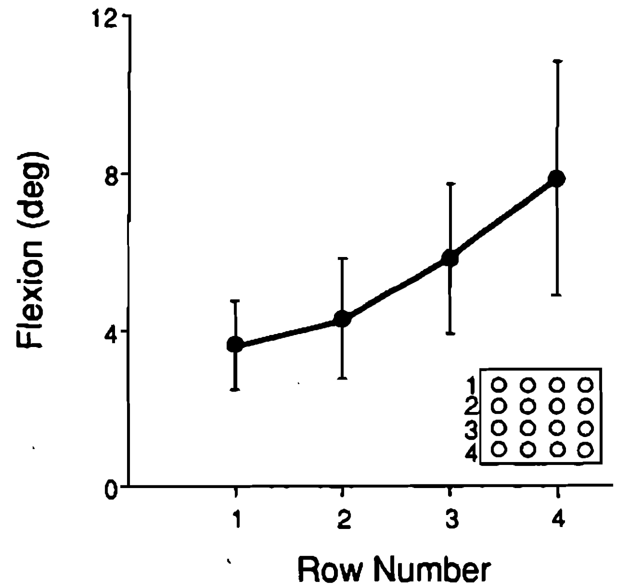

Figure 3. Average fundamental frequency magnitude for each element increased as wrist flexion angle increased, when grasping pegs from Row 1 to Row 4 (5 subjects). Error bars indicate one standard deviation.

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 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.

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 latterally 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:

Reach for peg
Grasp peg
Move peg
Position Peg
Release peg

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 $\Delta f = 0{\cdot}059$ 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 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 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 ($F(1,4) = 23{\cdot}54$, $p < 0{\cdot}01$). The fundamental frequency mean magnitude increased from 2·5° (SD = 1·6°) for Row 1 to 18·0° (SD = 3·1°) for Row 4 ($F(3,12) = 34{\cdot}22$, $p < 0{\cdot}001$), 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 ($F(1,4) = 1{\cdot}05$, $p < 0{\cdot}5$).

These findings indicated that spectrum DC components can independently measure sustained posture while the AC components measured repetitive

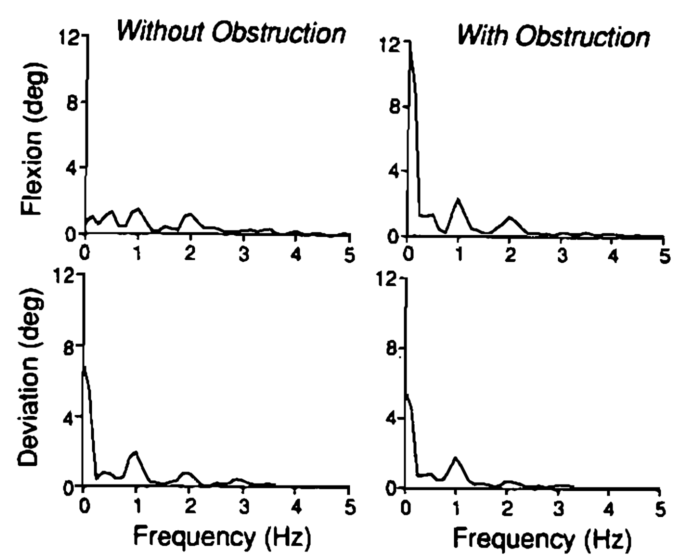

Figure 4. Representative spectra of wrist flexion/extension and ulnar/radial deviation (including DC component) for lateral peg transfers, both with and without an obstruction bar (1 subject). DC component magnitude for wrist flexion/extension is completely abated when the obstruction causing sustained flexion was removed.

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.

3.3. *Experiment 3: Two subcycles contained with 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:

Reach for Peg
Grasp Peg
Move Peg } 2×
Position Peg
Release Peg

Reach for Peg
Grasp Peg
Move Peg } 2×
Position Peg
Release Peg

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 $T_s = 20$s, and the frequency resolution was $\Delta f = 0{\cdot}029$ Hz for a 30 Hz bandwidth.

The resulting time series and corresponding power spectra are shown in figure 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 5). Spectra fundmental 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 $4 \times 1{\cdot}2$ s $= 4{\cdot}8$ 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 ($F(1,8) = 1{\cdot}907$, $p < 0{\cdot}5$) 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 *et al.* 1991). They

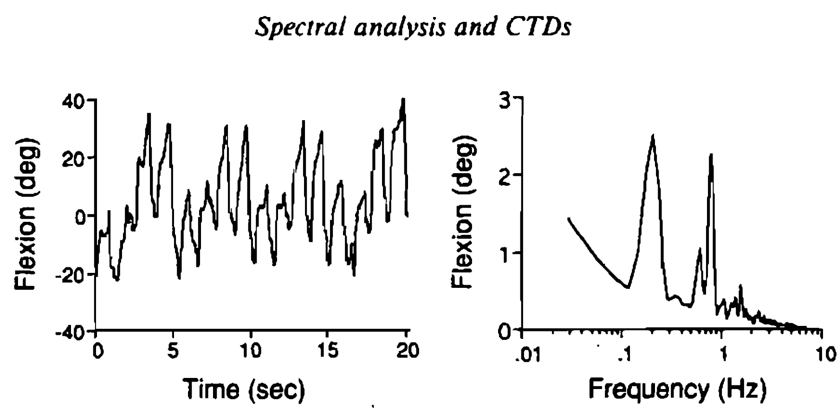

Figure 5. Representative time series and spectra for transferring pegs when subcycles are repeated four times within a fundamental cycle (1 subject). Spectrum contains two peaks at 0·21 Hz for the fundamental cycle repetition frequency, and at 0·83 Hz for the subcycle repetition frequency.

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 activites 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 repetitivness, 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 surpases 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.

Acknowledgements

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