ERGONOMICS, 2000, VOL. 43, NO. 1, 106–132

Comparison between using spectral analysis of electrogoniometer data and observational analysis to quantify repetitive motion and ergonomic changes in cyclical industrial work

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Keywords: Cumulative trauma; Repetitive motion; Posture; Job analysis; Electrogonimeters.

Spectral analysis of continuously measured joint angles using an electrogoniometer was considered as a potentially efficient method for quantifying exposure to physical stress in repetitive manual work. The method was previously demonstrated in the laboratory but has not yet been tested extensively in the field. Spectral analysis was compared against observational analysis, consisting of time-and-motion study and posture classification. Six industrial jobs were selected: (1) press operation, (2) large parts hanging, (3) product packaging, (4) small parts hanging, (5) parts counting and sorting and (6) construction vehicle operation. The posture angle data were synchronized with activities on the video using an interactive multimedia video data acquisition system. Motion for every joint was analyzed using both spectral analysis and observational analysis. Joint angles for the wrist, elbow and shoulder were directly measured using electrogoniometers. Visual posture classification involved determining joint angles from a frozen videotape image sampled three times per s. Repetitiveness was quantified for observational analysis using time study to measure the frequency that specific motions repeat, while spectral analysis measured repetitiveness as the frequency where spectral peaks occurred. Spectral analysis agreed closely with observational analysis. Correlation between the repetition frequencies obtained using time study and spectral analysis was 0.97, with no statistically significant difference observed. Average sustained posture was quantified as the mean, and posture deviation as the RMS angle of joint motion. No statistically significant differences between data obtained using posture classification or spectral analysis were observed for either posture deviation or sustained posture. Since posture classification was very limited in resolution and often contained measurement errors caused by poor joint visibility, the correlation between the postural classification and spectral analysis was 0.77 for sustained posture and 0.53 for posture deviation. When considering only large motions that exceeded the posture classification angle precision, the correlation between postural classification and spectral analysis was 0.81 for sustained posture and 0.81 for posture deviation. Spectral analysis of electrogoniometer data were, therefore, an efficient method for analyzing repetitive manual work that obtained equivalent results, and was more precise than observational analysis.

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Ergonomics ISSN 0014-0139 print/ISSN 1366-5847 online © 2000 Taylor & Francis Ltd
http://www.tandf.co.uk/journals/tf/00140139.html

1. Introduction

Observational analysis is a widely used method in ergonomics for investigating physical stress in the workplace. Work methods analysis has its roots in time-and-motion study (Gilbreth and Gilbreth 1917, Barnes 1968, Neibel 1988), and is often used to determine the work content and the time to accomplish industrial tasks (Habes and Putz-Anderson 1985, Armstrong *et al.* 1986). Although time study measures the temporal aspects of work, it does not by itself quantify information about motions. Conventional observational analysis in ergonomics includes a combination of posture classification for measuring the magnitude of motions, and time-and-motion study for measuring repetition and duration.

Observational methods use visual estimations to quantify postures and movements as an objective quantification of physical stress (Priehl 1974, Karhu *et al.* 1977, Armstrong *et al.* 1979, 1986, Corlett *et al.* 1979, Habes and Putz-Anderson 1985, Drury 1987, Keyserling *et al.* 1991). The simplest observation techniques involve dichotomous assessment of physical factors such as posture and force (Armstrong *et al.* 1986, Wiktorin *et al.* 1995). The method by itself, however, does not quantify the magnitude of physical stress with precision. The most detailed observation analysis usually involves video taping the work activity and laboriously reviewing the video recordings every few frames, or in slow motion to estimate the stresses on the body over time.

A commonly used observational approach is posture classification (Priehl 1974, Karhu *et al.* 1977, Armstrong *et al.* 1979, 1982, Corlett *et al.* 1979, Keyserling 1986). Priehl (1974) developed the 'posturegram' method that coded the location and movement of body parts in three coordinate planes. Karhu *et al.* (1977) used a method in which specific postures were assigned an ordinal value. Another method called posture targeting was similar to the posturegram (Corlett *et al.* 1979). Posture targeting had continuous posture resolution in the vertical and horizontal planes with postures recorded at variable intervals using time sampling. A posture classification method introduced by Wiktorin *et al.* (1995) recorded the relative position of the hand to the body, however individual joint angles were not recorded. The Finnish Institute of Occupational Health (1992) whole-body coding system called OWAS, coded observed posture, force and work phase using a six-digit number. An observation method similar to OWAS called Rapid Upper Limb Assessment (RULA), assessed posture, forces and muscle activities for the upper limb (McAtamney and Corlett 1993). The method involved pictorial and tabular checklists and a numerical score associated with each checked item for computing a combined score.

Posture classification has been adopted by numerous studies of repetitive motions associated with upper extremity musculoskeletal disorders. Armstrong *et al.* (1979, 1982) recorded tasks on cinematic film and later used videotape (Silverstein *et al.* 1986, 1987). The postures were analyzed at a sample rate of three frames per s, with angles classified into discrete intervals. Keyserling (1986) introduced a computerized observational method using video for upper torso motions. Frequency, duration and the number of postural changes were quantified using this method based on postures categorized by discrete intervals. Analysis of each joint required replay of the videotape.

Although observational posture classification methods have been useful for studying postural stress and repetitive motion, these measurements are extremely limited in their ability fully to characterize dynamic physical stress. Observational methods lack precision, take a great deal of time to perform, require highly trained observers and are subject to analyst experience and biases. The time and resources necessary for conducting detailed posture classification studies has made it impractical for most industrial applications and cost prohibitive for large-scale epidemiological investigations of the causal and aggravating factors of work related musculoskeletal disorders in repetitive manual work. Owing to the long analysis time, the amount of data analyzed is often limited to just several representative work cycles, which is a small percentage of the total task that can be observed on tape (Armstrong *et al.* 1979, 1982, Silverstein *et al.* 1986, 1987).

Since posture classification estimates joint angle solely through observation, the ability to make accurate estimates is dependent on the analyst's training and experience. In addition, a view perpendicular to the plane of motion is necessary to avoid parallax error. This is not always possible in practice. Ericson *et al.* (1991) observed 5° median error for static postures and 10 – 13 for dynamic postures. Geniady *et al.* (1993) obtained much smaller mean error for upper arm posture estimates of 1.3 from a group of untrained analysts. However, observers over-estimated angles ranging from 1 to 60°, and under-estimated angles ranging from 61 to 180°.

Direct posture measurements, including goniometers, inclinometers, accelerometers and optoelectronics devices, have been considered as an alternative to posture classification (Plagenhoef 1971, Morris 1973, Nordin *et al.* 1984, Armstrong *et al.* 1988, Mathiassen and Winkel 1991, Moore *et al.* 1991, Marras and Schoenmarklin 1993, Radwin and Lin 1993, Kluth *et al.* 1994, Radwin *et al.* 1994, Andersson *et al.* 1996, Hansson *et al.* 1996). Electrogoniometers can continuously measure the included joint angle between limbs (Plagenhoef 1971, Armstrong *et al.* 1988, Moore *et al.* 1991, Marras and Schoenmarklin 1993, Radwin and Lin 1993, Radwin *et al.* 1994, Wells *et al.* 1994, Hansson *et al.* 1996). Direct posture measurement has been criticized as being expensive, time-consuming to use and calibrate, and produces a great amount of data for analysis (Kilbom 1994). The large quantity of data collected from direct measurement proved the greatest hindrance. Moore *et al.* (1991) and Wells *et al.* (1994) collected electrogoniometer data for quantifying motions, and EMG data for quantifying force, but due to the demanding time constraints of the data analysis, the amount of data analysis was limited to the 5-min segments of video that best represented the task. Marras and Schoenmarklin (1993) reduced the data by computing angular acceleration from electrogoniometers measuring wrist angles. Acceleration, however, is difficult directly to relate to joint angles and corresponding job design factors affecting posture, repetition and duration for targeted intervention. A metric relating directly to joint angles is, therefore, the most desirable.

Spectral analysis of continuously recorded kinematic data has been suggested as a convenient method for computing repetition, posture deviation and sustained posture for cyclical motions (Radwin and Lin 1993, Radwin *et al.* 1994). Spectral analysis has been used successfully in the laboratory for characterizing repetitive motion in simulated cyclic industrial tasks. Radwin and Lin (1993) demonstrated the use of spectral analysis of wrist angle data for resolving differences in repetitiveness, posture deviation, and sustained posture for specific aspects of repetitive manual tasks. The DC component of the spectrum corresponded to the average posture. The peak AC component frequencies corresponded to the frequency or repetitiveness of the cyclical movements. The RMS magnitude of each spectral component indicated posture deviation for the corresponding repetition rate. When RMS approaches zero, the DC component indicates a constant posture that is sustained. Conventional signal processing methods provide the ability conveniently to average the spectra for a large number of task cycles and common elements into a single spectrum even with varying element or cycle times (Radwin *et al.* 1994). The spectral method is particularly attractive because it can directly ascertain posture and repetition from electrogoniometer data in the same analysis.

The current study compares the spectral analysis method using electrogoniometric data against observational job analysis. Because it has been widely applied (Habes and Putz-Anderson 1985, Armstrong *et al.* 1986, Silverstein *et al.* 1986, 1987), the posture classification method developed by Armstrong *et al.* (1982) was used as the reference instrument. Jobs from several industries and different tasks were studied and the results were compared using each method.

2. Methods

2.1. *Equipment*

Joint angles were measured using commercial electrogoniometers (Either Penny and Giles Biometrics, Ltd, UK or Exos, Inc., Woburn, MA, USA). Motions included wrist flexion/extension, ulnar-radial deviation, forearm rotation, elbow flexion/extension, shoulder flexion/extension and shoulder adduction/abduction. Electrogoniometers like the Penny and Giles have noted limitations. Studies of these goniometers by Casolo and Legnani (1990) and Buchholz and Wellman (1997) found that errors were greatest at the extreme angles ($> \pm 45°$). By calibrating the goniometer within the range of motion for the tasks under study (usually $< \pm 45°$) these errors can be reduced.

The electrogoniometers were attached to the skin using double-sided adhesive tape. Surgical tape was also used to secure the electrogoniometers and cables. Angle calibration was performed for each joint after the electrogoniometers were mounted on the limb over the respective joints. The joints were positioned in several angles consistent with the joint range of motion for the task. The angles were measured using a manual goniometer and corresponding voltages for each joint were used to calibrate the electrogoniometers using linear regression. The mean standard error was 6.36° for the wrist, 6.18° for the elbow and 17.45° for the shoulder. Over the range of motion, the error was $< 5\%$ for elbow, 7% for the wrist and 10% for the shoulder.

Video cameras recorded workers performing the jobs under study. Two camera views were mixed to produce a split screen image of the worker. The posture data were digitized and sampled using a custom video-based data acquisition and extraction system that recorded the electrogoniometer analogue signal and synchronized it with the work activities observed in the video (Radwin and Yen 1993, Yen and Radwin 1995). The signals were sampled at 60 points/s, digitized, encoded and recorded on the audio track of VHS tape along with the video image.

2.2. *Procedures*

Six industrial jobs were selected for study based on workstation features or job requirements that could emphasize the differences in sustained posture, repetition rate or posture deviation. These jobs are summarized in table 1. All jobs were considered highly repetitive. The supervisor for each job recommended experienced employees who were asked to volunteer with informed consent and without remuneration other than their regular salary. The operators were asked to perform their job as normal. In some cases a workstation intervention was also tested, such as standing on a platform or using an alternative work method. The experimental protocol was approved by the University of Wisconsin Human Subjects Review Board.

All the jobs involved repetitive motions, permitting the data to be partitioned into cycles. A time study was performed separately for each joint. Cycle breakpoints were assigned to distinctive motions observed in the video for the respective joint. The number of cycles required to achieve ±5% mean error with 95% confidence was determined (Niebel 1988). Table 2 shows the quantity of data analyzed for each job. The same analyst assigned all of the cycle breakpoints for all six jobs. Segments of electrogoniometer data were extracted from the videotape based according to the corresponding cycle breakpoints.

Table 1. Description of the jobs studied.

Job name	Job description	Study conditions and levels
Press operation	Pick up part in one hand and transfer it to a tool in the other Transfer the part to a press fixture Activate press by depressing buttons with both hands	platform height (0 or 15 cm) operator sits
Large parts hanging	Pick up parts from a bin and hang on hooks located at two different heights travelling on a vertical conveyor system	hook height (low and high) platform height (0 or 30 cm) operator stands
Product packaging	Pick up product off conveyor and stack in a box (The box was angled so the open end faces the worker)	position (seated or standing)
Small parts hanging	Pick up parts from a tray and hang on hooks located at three different heights travelling on a vertical conveyor system	hook height (low, middle, high) hand use (right, left) operator was seated
Parts counting and sorting	Count six parts and slide into bins on conveyor for packaging	sorting method (single or multiple bins)
Construction vehicle operation	Operate a wheel loader vehicle for a repetitive load, unload task	steering system (wheel or joystick)

Table 2. Number of cycles analyzed for each job.

	Amount of data analyzed		
Job	Time (min)	Average cycle time (s)	No. of cycles
Press operation	43	5.29	406
Large parts hanging	24	5.79	322
Product packaging	72	11.27	305
Small parts hanging	15	11.25	80
Parts counting and sorting	14	1.82	201
Construction vehicle operation	69	28.93	139

A computer-controlled VCR (Panasonic AG-7350, Secaucus, NJ, USA) enabled the analyst to review the tape while observing the work activities at any desired speed or arbitrary sequence (real-time, slow motion, fast motion or frame-by-frame in either forward or reverse direction). The time study was performed by interactively identifying distinct movements that indicated the start of an element in a particular video frame. A computer program maintained a table of the video timecodes for all the element breakpoints to compute elemental times.

The spectral analysis method involved calculating power spectra for each cycle of sampled electrogoniometer data and averaging over all the cycles into a single spectrum (Radwin *et al.* 1994). The one-cycle data segments were filtered with a Hanning window to reduce end-point effects. The windowed data were then zero padded so all the cycle segments were the same length. The resulting spectra, therefore, had the same frequency resolution so averaging could be applied. Three parameters were determined from the averaged spectra. Repetition rate was the frequency (Hz) where a spectral peak occurred. Posture deviation was expressed in terms of RMS (°) and the average sustained posture was determined from the spectrum DC (0 Hz) component (°). The spectrum parameters were compared against conventional observational analysis.

Observational analysis included a time-and-motion study to determine the repetition rate for each joint based on the average inverse of the time interval between specific joint motions for a particular action. Most of the jobs studied contained single element cycles. In cases where there were subcycles, additional time elements were included to quantify the subcycle frequencies. Upper extremity postures were coded by joint location about three axes of rotation for the shoulder, two axes for the elbow and two axes for the wrist (Armstrong *et al.* 1982). Postures corresponding to each axis of rotation were assigned one of three-to-six values corresponding to joint position. A summary of the categories and corresponding levels for each articulation are shown in table 3.

The observational analyses were conducted from two simultaneous views of the workers from videotapes. Adequate lighting was used to produce clear and good contract video recordings. All the workers wore clothing that did not restrict movement or obscure the body joints of interest. The analyst estimated joint angles by observing the posture every tenth video frame (30 frames/s) and indicating the appropriate angle for each joint. This produced a 3 Hz sampled time series.

A computer program was written to help implement the posture classification analysis using the computer-controlled VCR. The program displayed joint posture classifications for the shoulder, elbow, forearm and wrist. The desired joint angles were selected by clicking the computer screen cursor on checkboxes associated with the respective joint angle. After all the postures were entered for the current video frame, the VCR was automatically advanced 10 video frames for the next sample.

The posture classification time series data were partitioned into segments based on the same cycle breakpoints used for the spectral analysis method. The average sustained posture (°) was calculated from the arithmetic mean of the time series over each cycle. The joint deviation in RMS degrees was calculated from the corresponding joint posture classification time series. Since the electrogoniometer data were digitized at 60 samples/s with 256 amplitude levels (8 bits), while posture classification data were collected at 3 samples/s with at most six magnitude levels (depending on the joint), the electrogoniometer data were re-sampled to the same

Table 3. Posture classification articulation levels.

Articulation	Posture classification range					
Shoulder flexion extension	flex (< 40°)	45° (40 – 60°)	90° (60 – 120°)	135° (120 – 160°)	neutral (160 – 200°)	extend (> 200°)
Shoulder adduction, abduction	abduct (< – 90°)	45° (– 90 – – 40°)	neutral (– 40 – 10°)	adduct (10 – 60°)		
Elbow angle	flex (> 100°)	90° (100 – 70°)	45° (70 – 35°)	extend (< 35°)		
Forearm rotation	prone (< – 15°)	neutral (– 15 – 45°)	supine (> 45°)			
Wrist deviation	radial (< – 5°)	neutral (– 5 – 15°)	ulnar (> 15°)			
Wrist angle	flex (< – 45°)	45° flex (– 45 – – 15°)	neutral (– 15 – 10°)	45° extend (10 – 45°)	extend (> 45°)	

time and amplitude resolution as posture classification for each joint for direct comparison.

Analysis of variance for determining statistically significant differences between methods and task conditions were computed independently for the dependent variables of posture deviation, sustained posture and repetition frequency. Analysis method and articulation were the independent variables. Correlations and linear regressions were performed between the frequency, mean and RMS posture resulting from each analysis method.

3. Results

3.1. *Comparison between analysis methods*

Comparisons between the observation and spectral analysis methods for each joint, task condition and job are summarized for RMS posture deviation in table 4, sustained posture in table 5 and repetition frequency in table 6. RMS degrees represents the magnitude of motion as quantified by the amplitude level of the peak frequency component of the spectrum. Analysis of variance for spectral analysis parameters are also considered for specific task conditions, stratified by joint. Owing to range limitations of the electrogoniometer, data for forearm rotation was possible only for the construction vehicle operation job.

3.2. *Spectral analysis*

The following section describes spectral analysis results for specific joints, jobs and selected differences in task condition, ergonomic interventions and work methods.

3.2.1. *Press operation*: The press operation job was first performed as usual and then with the operator standing on a 15 cm high platform to locate the hooks near elbow height. Three joint motions were measured: wrist flexion/extension, ulnar/radial deviation and elbow flexion/extension. A detailed summary of the results for the press operation job is in tables 4 – 6.

The spectrum of the electrogoniometer signals revealed harmonic peak frequencies when there were subcycle's motions (i.e. repetition within a cycle) when the signal was segmented by cycles. The lowest peak frequency was the fundamental, corresponding to the cycle frequency, and the harmonic peak frequency indicated repetitive subcycle motions. A time-and-motion study for the activities corresponding to these subcycles is summarized in table 6. The press operation had a 0.5 Hz fundamental elbow flexion repetition frequency and a 1 Hz subcycle frequency. The spectrum shown in figure 1 was segmented by cycles. A secondary peak two times the fundamental frequency indicates that a motion within the cycle is repeated twice. Spectral analysis revealed subcycle frequencies when elbow flexion/extension was measured while the operator worked without a platform, and for wrist flexion/extension and elbow flexion/extension when a platform was used (figure 1).

The electrogoniometric method was capable of quantifying small but statistically significant posture differences between platform use conditions. Greater posture deviation RMS levels were observed for elbow flexion (F(1,388) = 63.92, $p < 0.05$) without platform use, considering the small difference in magnitude (table 4). Ulnar-radial deviation RMS was similarly greater when the platform was used (F(1,388) = 205.04, $p < 0.05$). A small statistically significant reduction of $< 1^\circ$ RMS was also observed for wrist flexion when the platform was used (F(1,388) = 19.93, $p < 0.05$).

Table 4. Spectral analysis (SA) and posture classification (PC) comparison for joint deviation (RMS degrees).

		Wrist				Elbow		Forearm		Shoulder			
		Rad, Ulnar		Flex, Ext		Flex, Ext		Rotation		Abd, Add		Flex, Ext	
Job	Condition	SA	PC	SA	PC	SA	PC	SA	PC	SA	PC	SA	PC
Press operation	platform	8	13	8	0	11	33	–	–	–	–	–	–
	no platform	7	14	8	0	12	38	–	–	–	–	–	–
Large parts hanging	platform top hook	11	0	13	2	25	21	–	–	4	0	19	20
	no platform top hook	12	0	14	3	28	20	–	–	5	0	35	37
	platform bottom hook	10	0	12	2	22	20	–	–	4	0	17	19
	no platform bottom hook	12	0	13	2	25	20	–	–	6	0	26	29
Product packaging	sitting	5	4	9	21	10	29	–	–	4	10	19	25
	standing	4	4	9	21	10	27	–	–	4	3	17	22
Parts counting and sorting	single bin	5	1	9	11	11	31	–	–	4	0	26	17
	multiple bins	6	7	11	18	9	28	–	–	3	1	18	18
Construction vehicle operation	wheel steering	5	0	4	4	7	37	10	12	4	4	9	22
	stick steering	12	0	6	0	3	0	8	38	2	0	0	0

– Data not available.

Table 5. Spectral analysis (SA) and posture classification (PC) comparison for sustained posture (degrees).

		Wrist				Elbow		Forearm		Shoulder			
		Rad, Ulnar		Flex, Ext		Flex, Ext		Rotation		Abd, Add		Flex, Ext	
Job	Condition	SA	PC	SA	PC	SA	PC	SA	PC	SA	PC	SA	PC
Press operation	platform	6	– 10	2	0	55	51	–	–	–	–	–	–
	no platform	14	– 20	22	0	48	54	–	–	–	–	–	–
Large parts hanging	platform top hook	– 23	0	19	1	61	70	–	–	1	0	– 3	18
	no platform top hook	2	0	18	0	79	75	–	–	5	0	29	37
	platform bottom hook	– 23	0	20	1	55	70	–	–	0	0	13	17
	no platform bottom hook	4	0	16	1	83	76	–	–	0	0	26	26
Product packaging	sitting	3	1	21	11	56	54	–	–	13	3	48	29
	standing	– 2	– 1	30	16	52	55	–	–	19	1	50	21
Parts counting and sorting	single bin	0	0	– 1	– 2	8	28	–	–	18	0	40	36
	multiple bins	0	– 3	– 29	– 14	25	67	–	–	8	0	– 4	11
Construction vehicle operation	wheel steering	– 17	0	– 30	1	15	51	– 81	– 87	45	1	63	24
	stick steering	– 24	0	13	0	68	90	– 3	– 24	42	0	41	0

– Data not available.

Table 6. Spectral analysis (SA) and time study (TS) comparison for repetition frequency (Hz).

		Wrist				Elbow		Forearm		Shoulder			
		Rad, Ulnar		Flex, Ext		Flex, Ext		Rotation		Abd, Add		Flex, Ext	
Job	Condition	SA	PC	SA	PC	SA	PC	SA	PC	SA	PC	SA	PC
Press operation	platform	0.395	0.467	0.190	0.184	0.190	0.239	–	–	–	–	–	–
	no platform	0.391	0.495	0.176	0.182	0.586	0.550	–	–	–	–	–	–
Large parts hanging	platform top hook	0.234	0.462	0.468	0.462	0.410	0.446	–	–	0.468	0.454	0.468	0.465
	no platform top hook	0.498	0.430	0.468	0.422	0.380	0.433	–	–	0.352	0.428	0.439	0.436
	platform bottom hook	0.233	0.451	0.468	0.454	0.439	0.426	–	–	0.468	0.423	0.468	0.451
	no platform bottom hook	0.322	0.460	0.468	0.451	0.439	0.448	–	–	0.440	0.457	0.468	0.457
Product packaging	standing	0.293	0.274	0.117	0.115	0.088	0.115	–	–	0.147	0.115	0.410	0.565
	sitting	0.215	0.115	0.058	0.115	0.098	0.115	–	–	0.137	0.115	0.410	0.57
Parts counting and sorting	single bin	0.308	0.285	0.147	0.128	0.440	0.549	–	–	0.483	0.277	0.483	0.577
	multiple bins	0.176	0.285	0.147	0.128	0.117	0.128	–	–	0.147	0.128	0.176	0.285
Construction vehicle operation	wheel steering	0.129	0.003	0.119	0.022	0.130	0.310	0.041	0.040	0.165	0.036	0.182	0.298
	stick steering	0.089	0.000	0.084	0.000	0.068	0.000	0.085	0.120	0.121	0.000	1.533	0.000

– Data not available.

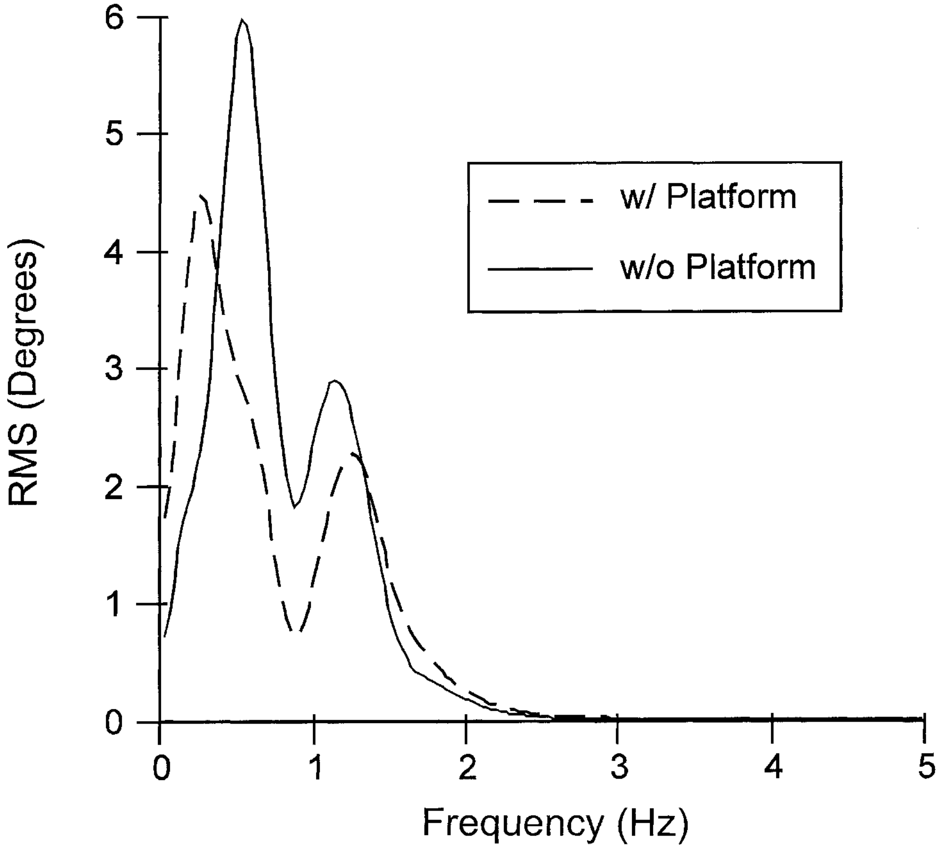

Figure 1. Elbow flexion/extension with subcycle components. The spectrum from the spectral analysis provides repetition rates for secondary peak frequencies from work elements within a work cycle in addition to the fundamental repetition frequency.

A statistically significant sustained posture reduction of 8° was observed for ulnar-radial deviation ($F(1,388) = 61.33$, $p < 0.05$), and a sustained posture reduction of 20° was observed for wrist flexion ($F(1,388) = 565.66$, $p < 0.05$) when the platform was used. A sustained posture increase of 7° for elbow flexion ($F(1,388) = 609.02$, $p < 0.05$) was also observed when the platform was used (table 6).

Ulnar/radial deviation was the only joint that had a significant 0.004 Hz reduction in repetition frequency when the platform was used ($F(1,274) = 4.20$, $p < 0.05$) which corresponded to a 26 ms difference in mean cycle times. The elbow flexion repetition frequency with the platform had a subcycle component at 1.030 Hz, which was not observed without the platform (table 6).

3.2.2. *Large parts hanging*: This job involved hanging stamped metal parts on different height hooks for subsequent painting. The job was studied both for the worker standing at floor level and standing on a 30 cm high platform. The intent of the platform was to relocate the hooks below mid-torso height. All joint motions were measured for the left upper limb. Results are included in tables 4–6.

In general, platform use had no effect on repetition frequency, and hook height had a minor effect on repetition frequency. The most noticeable hook height differences were revealed for ulnar-radial deviation, with 0.17 Hz less repetition frequency for the bottom hook (F(1,422) = 8.48, $p < 0.05$) which corresponded to a 1.1 s difference in mean cycle times. Repetition frequency for the top hook was 0.1 Hz less than the bottom hook by for shoulder adduction/abduction (F(1,422) = 7.21, $p < 0.05$) which corresponded to a 704 ms difference in mean cycle times and by 0.05 Hz less than the bottom hook for elbow flexion (F(1,422) = 4.92, $p < 0.05$) which corresponded to a 354 ms difference in mean cycle times. The wrist flexion repetition frequency when the platform was used was slightly less than when the platform was not used (F(1,422) = 6.55, $p < 0.05$) (table 6).

The platform reduced shoulder flexion sustained posture by 13° (F(1,426) = 16.17, $p < 0.05$). The platform, increased the shoulder adduction/abduction sustained posture angle by 4° (F(1,426) = 31.00, $p < 0.05$). The shoulder adduction/abduction sustained posture for the low hook was 3° greater (F(1,426) = 26.22, $p < 0.05$), and the elbow flexion sustained posture was 22° greater when the platform was used (F(1,426) = 202.38, $p < 0.05$). Sustained posture for shoulder flexion was 10° greater (F(1,426) = 138.83, $p < 0.05$), wrist flexion was 2° greater (F(1,426) = 7.14, $p < 0.05$), and ulnar-radial deviation was 25° (F(1,426) = 87.03, $p < 0.05$) for the high hook.

Shoulder flexion RMS was reduced by 16° for the high hook and by 9° for the low hook when the platform was used (F(1,426) = 34.69, $p < 0.05$). The shoulder flexion spectra are shown in figure 2. The high hook shoulder flexion RMS was 37° at the peak frequency and the low hook shoulder flexion RMS was 27° for the platform (F(1,426) = 121.89, $p < 0.05$). The high hook shoulder flexion RMS without the platform was 158° and the low hook shoulder flexion RMS was 71°. Platform use both wrist flexion RMS (F(1,426) = 15.66, $p < 0.05$) and elbow flexion RMS (F(1,426) = 28.34, $p < 0.05$) by 2°. The bottom hook level had less joint deviation than the top hook level by 1° for wrist flexion RMS (F(1,426) = 12.17, $p < 0.05$) and by 3° for elbow flexion RMS (F(1,426) = 33.61, $p < 0.05$).

3.2.3. *Product packaging*: The product-packaging job was studied both while the operator was both seated and standing. All joint motions for this job were measured for the right side of the body only. Subcycle frequencies were observed for wrist flexion, ulnar/radial deviation, elbow flexion, and shoulder adduction/abduction (table 6). A tertiary subcycle of 0.703 Hz was observed for wrist flexion when the operator was seated. The analyses for the product-packaging job are shown in tables 4 – 6.

Repetition frequency was not affected by seating conditions, with only elbow flexion having a 0.01 Hz greater fundamental frequency while standing (F(1,302) = 10.24, $p < 0.05$). The standing condition produced 5° less sustained posture for ulnar-radial deviation (F(1,605) = 120.13, $p < 0.05$), and 4° less sustained posture for elbow flexion (F(1,605) = 41.20, $p < 0.05$) (table 5). The seated condition produced 6° less sustained posture for shoulder abduction/adduction (F(1,605) = 13.83, $p < 0.05$) and 9° less sustained posture for wrist flexion (F(1,605) = 307.60, $p < 0.05$) (table 5).

In the seated position, 2° greater RMS deviation was observed for shoulder flexion (F(1,301) = 42.67, $p < 0.05$) and 1° greater RMS deviation for ulnar/radial deviation (F(1,301) = 23.23, $p < 0.05$). Statistically significant less RMS deviation

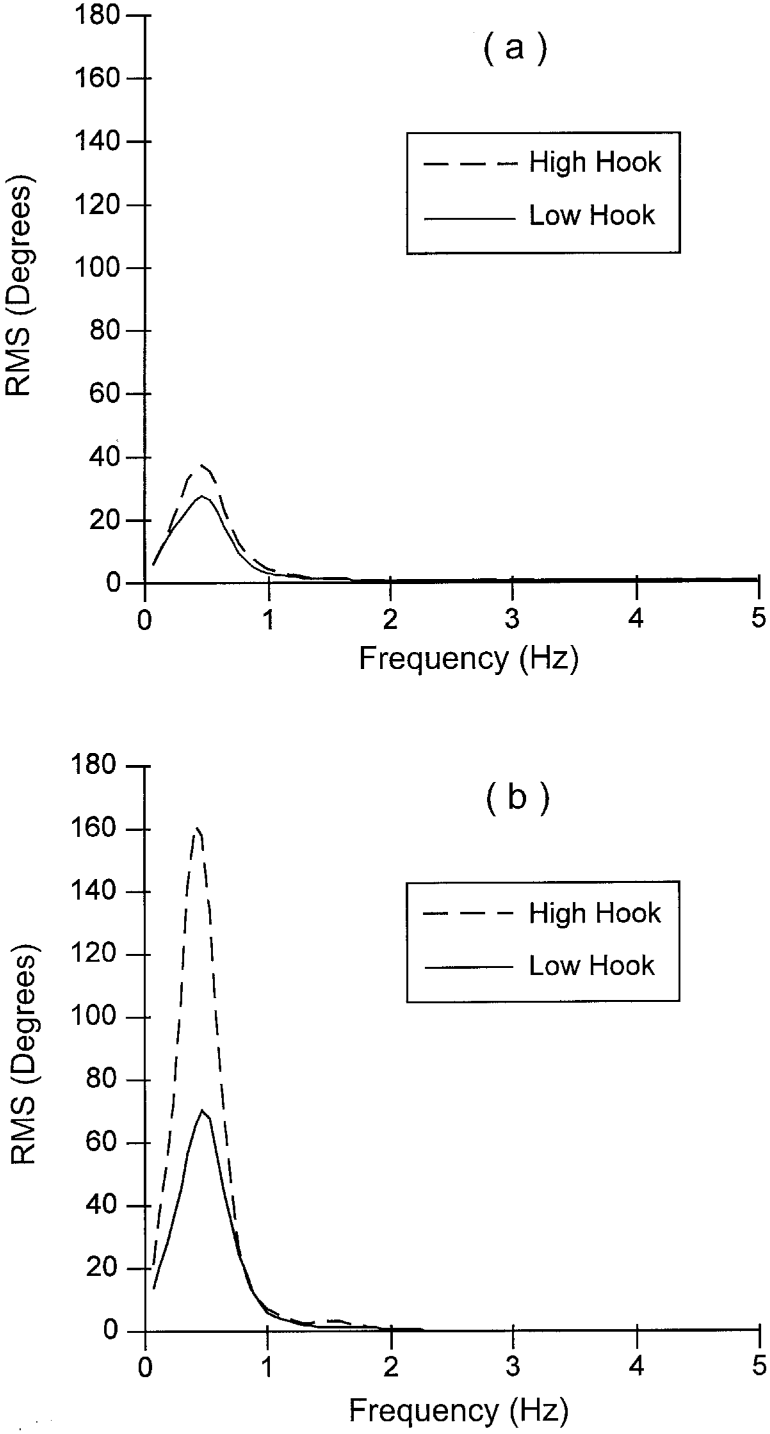

Figure 2. Shoulder flexion/extension for two platform and hook heights. The addition of the platform reduced the overall shoulder flexion angle as well as the relative hook difference. (a) With platform; (b) without platform.

was observed while standing for elbow flexion ($F(1,301) = 39.47$, $p < 0.05$) and for shoulder abduction/adduction ($F(1,301) = 14.67$, $p < 0.05$) (table 4).

3.2.4. *Small parts hanging*: Parts were hung at three different hook heights using both the right and left hands. Wrist flexion/extension and ulnar/radial deviations of both hands were measured for this job. The mean sustained posture, RMS deviation, and repetition frequency for wrist flexion/extension and ulnar/radial deviation are plotted against hook level in figure 3. The mean sustained posture, RMS deviation and repetition frequency for both wrist flexion/extension and ulnar/radial deviation are summarized in table 7.

No statistically significant repetition frequency differences were observed between the right and left hands for both wrist flexion/extension ($F(1,515) = 3.82$, $p \geqslant 0.05$) or ulnar/radial deviation ($F(1,513) = 0.00$, $p \geqslant 0.05$). Similarly no statistically significant differences in RMS deviation was observed between the right and left hands for ulnar/radial deviation ($F(1,513) = 1.70$, $p \geqslant 0.05$). The RMS deviation for the left hand wrist flexion/extension was 1° greater than for the right hand ($F(1,515) = 8.83$, $p < 0.05$).

The ulnar/radial deviation sustained posture was near neutral, but the left hand was 2° greater than the right ($F(1,513) = 28.69$, $p < 0.05$). The wrist flexion/extension sustained posture for the right hand was 20° less than for the left hand ($F(1,515) = 260.34$, $p < 0.05$).

RMS deviation for wrist flexion/extension was least for the low hook level and greatest for the medium hook level, with a 1° difference ($F(2,515) = 3.06$, $p < 0.05$). Average wrist flexion/extension for the high hook was 0.5°RMS between wrist flexion/extension for the other hook levels. RMS deviation angles for ulnar/radial deviation was least for the low hook level and greatest for the high hook level, with a 1° difference ($F(2,513) = 12.73$, $p < 0.05$).

Sustained posture for wrist flexion/extension was least for the low hook level and greatest for the medium hook level, with a 3° difference ($F(2,515) = 4.44$, $p < 0.05$). Average wrist flexion/extension for the high hook was only 0.1° less than for the medium hook level. Sustained posture angles for ulnar/radial deviation was least for the low hook level and greatest for the high hook level, with a 3° difference ($F(2,513) = 14.12$, $p < 0.05$) and the medium hook angle near neutral wrist posture.

No statistically significant differences in repetition frequency were observed for wrist flexion/extension ($F(2,515) = 1.54$, $p \geqslant 0.05$). Repetition frequency for ulnar/radial deviation was greatest for the low hook level and least for the high hook level ($F(2,513) = 3.88$, $p < 0.05$) with a 0.5 Hz difference between the low and medium hook frequencies, and less than a 0.1 Hz difference between the medium and high hook frequencies.

3.2.5. *Parts counting and sorting*: The parts counting and sorting job involved reaching and grasping up to six parts (2.5 cm long, 0.5 cm diameter and 5 g weight) from a pile of parts located arms length from the operator, and moving them toward the body to place them into a bin on a moving conveyor. Two different work methods were utilized for this job. The single bin method involved first counting six units and then sliding the pieces into the bin. The multiple bin method was used when the worker picked up a handful of parts, dropped six pieces one at a time into the bin and then moved to the next bin and continued dropping pieces into a bin until the hand was empty. All six joint motions were

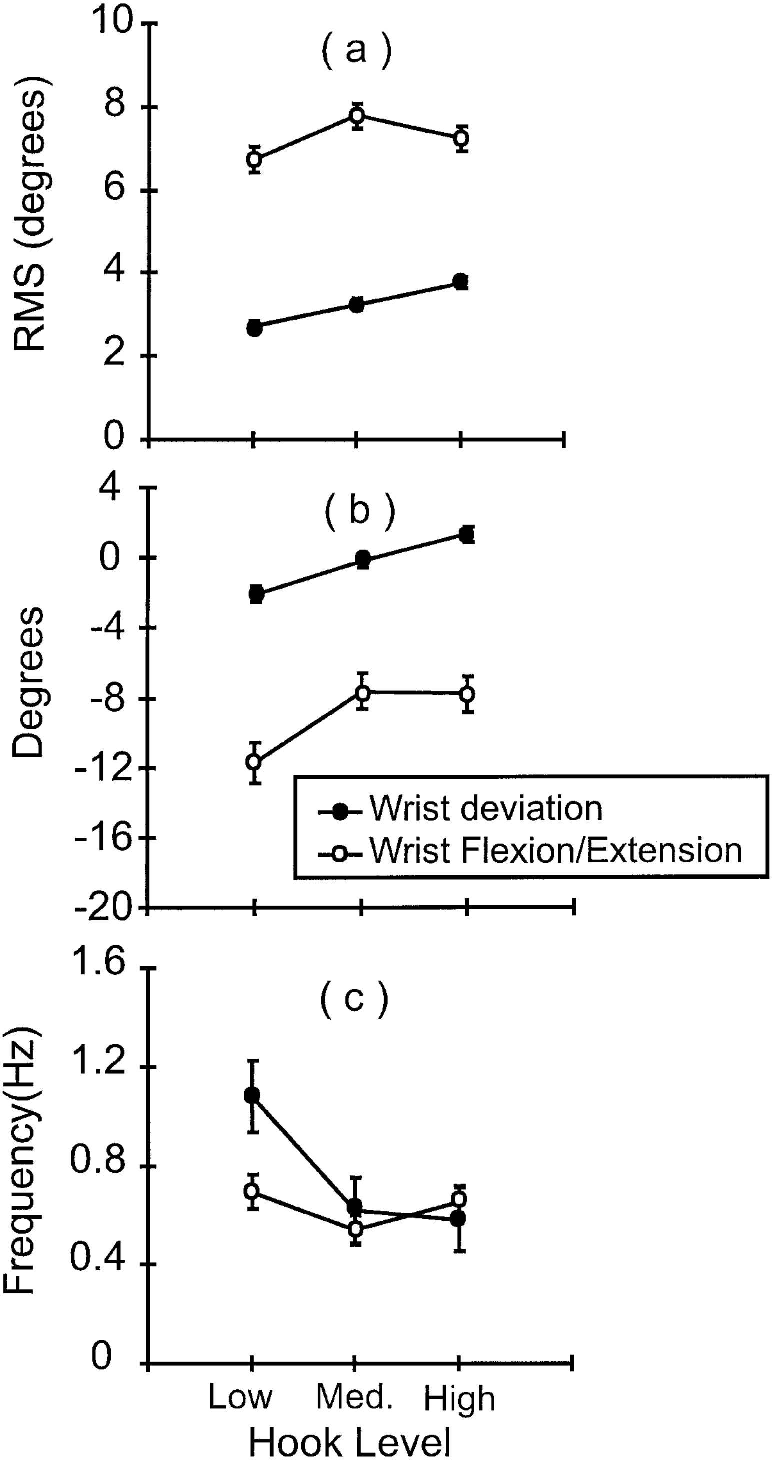

Figure 3. (a) Wrist posture deviation, (b) sustained posture and (c) repetition frequency comparison for hook level height in the small part hanging job.

Table 7. Wrist posture deviation, sustained posture and repetition frequency comparison for hand use in the small parts hanging job.

Joint	Hand	Posture deviation (RMS degrees)	Sustained posture (degrees)	Repetition frequency (Hz)
Wrist	right	6.731 (0.244)	– 19.010 (0.868)	0.702 (0.052)
Flexion/extension	left	7.761 (0.247)	0.900 (0.878)	0.556 (0.053)
Ulnar/radial	right	3.333 (0.117)	– 1.679 (0.361)	0.761 (0.110)
Deviation	left	3.117 (0.118)	1.065 (0.364)	0.760 (0.111)

measured on the right side of the body. The analysis for the parts packaging job is summarized in tables 4–6.

Different shoulder flexion/extension repetition rates were observed between the two work methods (figure 5a). The shoulder flexion/extension spectrum had a peak at 0.176 Hz for the multiple bin method and a peak at 0.483 Hz for the single bin method. An increase of 0.3 Hz in the repetition frequency for the single bin method was observed for shoulder flexion ($F(1,68) = 28.15$, $p < 0.05$), shoulder abduction/adduction ($F(1,68) = 38.07$, $p < 0.05$) and elbow flexion ($F(1,68) = 21.96$, $p < 0.05$). Although small the difference in wrist flexion repetition frequency was statistically significant for work method ($F(1,68) = 7.17$, $p < 0.05$).

Sustained posture for the multiple bin method was reduced 10° for shoulder abduction/adduction ($F(1,68) = 223.10$, $p < 0.05$) and reduced 40° for shoulder flexion ($F(1,68) = 62.68$, $p < 0.05$). Alternately, sustained wrist flexion was 28° less ($F(1,68) = 188.86$, $p < 0.05$) and sustained elbow flexion was 17° less ($F(1,68) = 61.88$, $p < 0.05$) for the single bin than for the multiple bin method.

RMS deviation for all joints except shoulder abduction/adduction had statistically significant differences ($p < 0.05$) between work methods. The multiple bin method RMS deviation was 2° greater for wrist flexion ($F(1,68) = 5.44$, $p < 0.05$), and 1° greater for ulnar-radial deviation ($F(1,68) = 7.71$, $p < 0.05$) for the single bin method. RMS deviation was 3° greater for elbow flexion ($F(1,68) = 7.43$, $p < 0.05$), 8° greater for shoulder flexion ($F(1,68) = 36.07$, $p < 0.05$) and 1° greater for shoulder abduction/adduction ($F(1,68) = 9.24$, $p < 0.05$) for the single bin method.

3.2.6. *Construction vehicle operation*: This investigation considered two different types of wheel loader construction vehicles. One had a conventional wheel steering system and the other had a joystick steering system. Both vehicles were the same in all other ways. The motions measured for wheel loader operation were limited to an operator performing repetitive load/unload cycles in a similar manner using each vehicle. All six joint motions were measured on the left side of the body. Analyses summaries for the construction vehicle operation job are shown in tables 4–6.

The forearm rotation repetition frequency for the stick steering system was twice as great as for the wheel steering system ($F(1,335) = 6.02$, $p < 0.05$). Repetition frequency was 0.04 Hz less for the stick steering system than for the wheel steering system for ulnar/radial deviation ($F(1,111) = 4.82$, $p < 0.05$), wrist flexion ($F(1,95) = 30.41$, $p < 0.05$) and elbow flexion ($F(1,70) = 13.20$, $p < 0.05$). Shoulder flexion repetition for the stick steering was eight times greater than for wheel steering ($F(1,93) = 4.22$, $p < 0.05$) but the magnitude of the motion was small (table 8).

Stick steering sustained posture angles increased by 7° for ulnar-radial deviation ($F(1,111) = 5.24$, $p < 0.05$). Stick steering sustained posture decreased by 78° for forearm rotation (F(1,70) = 19.71, $p < 0.05$). Stick steering RMS deviation decreased by 4° for elbow flexion (F(1,47) = 422.90, $p < 0.05$), 2° for forearm rotation (F(1,73.33) = 5.48, $p < 0.05$) and 9° for shoulder flexion (F(1,83) = 62.26, $p < 0.05$). Wheel steering RMS deviation was 7° less for ulnar-radial deviation (F(1,111) = 63.65, $p < 0.05$) and 2° less for wrist flexion (F(1,95) = 11.13, $p < 0.05$).

3.3. *Comparison between analysis methods*

3.3.1. *Repetition frequency*: Wrist flexion repetition compared between the press operation job and the large parts hanging job based on spectral peaks is shown in figure 4a. The press operation repetition frequency was 0.2 Hz, consisting of one wrist flexion every 5 s. The parts hanging job repetition frequency was 0.5 Hz, consisting of one wrist flexion every 2 s. Time study showed similar repetition frequency relationships (table 6). Repetition frequency was also compared between different work methods (figure 4b). Shoulder flexion for parts counting and sorting revealed a repetition frequency more than twice as fast for the single bin method than as the multiple bin method. A similar relationship was seen in the time study results (table 6).

Comparison of repetition frequencies between time-and-motion study and spectral analysis pooled across all the joints and jobs ($n = 60$) had a Pearson correlation coefficient of 0.97. The difference between spectral analysis and time-and-motion study repetition frequencies was not statistically significant (F(1,36) = 0.15, $p = 0.05$). The mean absolute difference between the time-and-motion study repetition frequency and the peak spectral component frequency was 0.069 Hz (SD = 0.176 Hz). A scatter plot and linear regression between repetition frequencies obtained for the two analysis methods is plotted for all joints and jobs in figure 5a. The regression slope was 0.95, indicating a close correspondence between the two analysis methods.

3.3.2. *Sustained posture and RMS deviation*: The Pearson correlation coefficients between posture classification and spectral analysis sustained postures were 0.77. The correlation for RMS deviation was 0.53. RMS deviation measurements were significantly different between spectral analysis and posture classification (F(1,36) = 4.58, $p < 0.05$). The mean absolute difference was 7.89° (SD = 7.35°). No statistically significant sustained posture difference (F(1,36) = 1.68, $p = 0.05$) was observed between spectral analysis and posture classification. The mean absolute difference was 15.31° (SD = 12.69°). A scatter plot and linear regression between posture classification and spectral analysis RMS deviation and sustained posture are shown in figure 5b and c respectively. The regression slope was 0.593 for RMS deviation and 0.91 for sustained posture. The 0.59 slope indicates that observational posture classification over-predicted posture deviation as measured directly using electrogoniometers by an average of 60%.

Correlation using a subset of the posture data that had a range of joint motion sufficiently large to be resolved by the posture classification angle partitions ($n = 12$ cases) was computed. The correlation coefficient for this data subset was 0.81 for sustained posture, and 0.81 for posture deviation. No statistically significant difference was observed between spectral analysis and posture classification for RMS deviation (F(1,22) = 0.06, $p = 0.05$) and sustained posture (F(1,22) = 0.06,

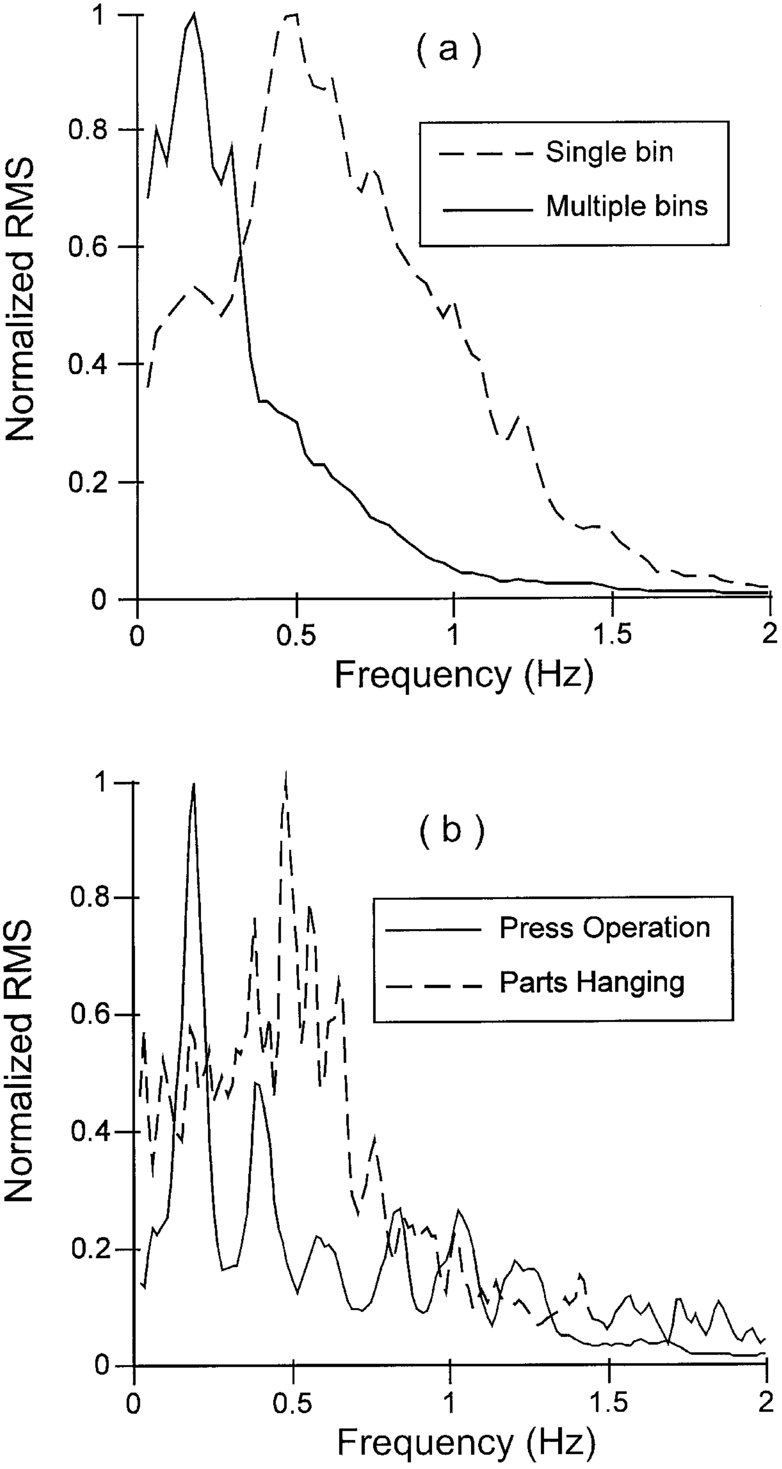

Figure 4. Frequency change in the spectra for (a) shoulder flexion using difference work method and (b) wrist flexion of two different jobs.

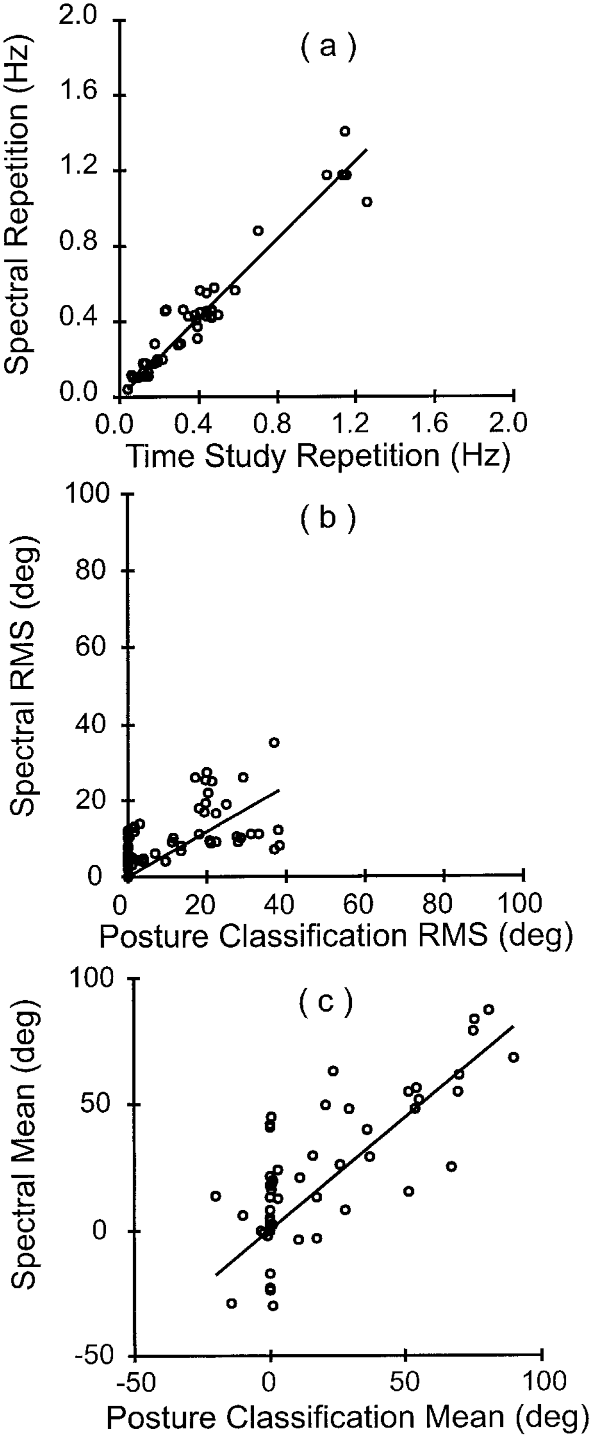

Figure 5. Comparison of spectral analysis and time-study for (a) repetition frequency (n= 60). Comparison of spectral and posture classification analysis for (b) postural deviation (n= 59) and (b) sustained posture (n= 59).

$p = 0.05$). The mean absolute difference was reduced to 3.80° (SD = 2.23°) for RMS deviation, and 13.84° (SD = 10.88°) for sustained posture.

Linear regression between posture classification and spectral analysis for RMS deviation and for sustained posture were computed using the data subset described above. No statistically significant difference (t(56) = 1.01; $p = 0.05$) was observed between the linear regression models for the full data set and the data subsets for posture deviation. A significant difference (t(56) = 2.27; $p < 0.05$) was observed between the full data and data subsets for the sustained posture linear regression models. The regression slopes for RMS deviation was 0.56 ($R^2 = 0.65$) and 0.949 ($R^2 = 0.64$) for sustained posture using the reduced data set.

4. Discussion

Spectral analysis was previously shown useful in the laboratory for quantifying repetitiveness in simple peg tasks (Radwin and Lin 1993). Posture magnitude and repetition rates were obtained directly from the spectra. The current study demonstrates that spectral analysis was similarly capable of quantifying differences in posture amplitude and repetition frequency for actual industrial jobs involving complex work parameters. Jobs with different task and workstation characteristics were compared based on sustained posture, RMS deviation and repetition frequency.

Spectral analysis indicated differences in operator motions for the same task using different equipment features. For example, the construction vehicle joystick-controlled steering system involved lateral rotation of the control stick. The control stick orientation and location required a relatively constant ulnar deviation angle, while the wheel steering ulnar deviation angle varied with steering posture. On average, the joystick control had an 8° greater sustained ulnar deviation angle than the wheel control. The forearm rotation angle changed from 81° pronation for the steering wheel to 3° pronation (0° neutral) for the joystick. These differences were directly quantifiable and observable in the electrogoniometric data.

The sustained ulnar deviation angle measured from the spectral DC component for the press operation was 8° less, and wrist flexion angle was 20° less with the use of the platform for relocating the operator relative to the press. A similar difference was observed for the sustained ulnar deviation angle using posture classification. However, posture classification did not detect any difference between platform usage for wrist flexion. Posture classification indicated differences in elbow flexion and forearm rotation for the construction vehicle operation, and ulnar-radial deviation for the press operation, but posture classification was unable to detect any changes in wrist flexion sustained posture for the press operation for the same number of observations. This was because of the differences in sustained posture could not be resolved by the posture classification precision used when the ranges of motion were less than the angle partition size.

The large parts hanging job demonstrated how spectral analysis may be used to differentiate joint motion among different workstation conditions. Not only were the shoulder flexion/extension amplitude differences between the platform heights distinguishable, so were the posture differences between the high and low hooks. The shoulder flexion/extension spectrum peak magnitude decreased by 121° for the high hooks, and by 44° for the low hooks when the platform was used (figure 2). Platform use reduced the overall shoulder flexion angles as well as the relative hook height differences. The difference in sustained shoulder flexion between the low and high hooks was 10° with the platform and 87° without the platform. The difference in shoulder flexion RMS between the low and high hooks was 2° with the platform and 9° without the platform.

The three hook heights for the small part-hanging job had small RMS deviation and sustained posture differences but spectral analysis was capable of revealing differences in wrist flexion/extension (figure 3). Posture classification was unable to quantify differences between these conditions and had difficulty representing the dynamic components of motion. As with sustained posture, small changes in motion were missed by posture classification when the ranges of motion were less than the posture angle partition size. Posture classification also misclassified small motions as sustained postures. This resulted in an inherent bias between the actual joint angle and the posture classification angle. When large magnitude joint motion are classified into angle partitions relative to the electrogoniometer data, the maximum error can be as great as half the angle partition range due to the precision of the posture classification instrument. When joint motion is misclassified into the neighbouring angle partition due to limits in precision of the posture classification instrument relative to joint motion magnitude, the error can be as great as 1.5 times the angle partition range.

Before the current study, the spectral analysis method has not been extensively tested in the field. Hansson *et al.* (1996) collected wrist motions using electrogoniometers in fish processing for up to 27 min. Power spectra were calculated for each half minute of data and averaged. Mean power frequency (MPF) was used as an index of repetitiveness and was observed related to the inverse of cycle time.

Different repetition rates were distinguished among the jobs studied and comparable with different work paces and joint motions measured using both time study and spectral analysis. The spectrum peak frequency was found to be a good indicator of repetition frequency, allowing comparisons of different jobs and work conditions (figures 1 and 5). Spectral analysis also provided information about subcycle frequency components (figure 1). Subcycles may be identified using time study but it is very time consuming since it involves identifying breakpoints that represent subcycles rather than cycles. Visual identification of secondary joint motion by observation is difficult when joint motions are not visually distinct. Although sometimes visually discernible, it was often difficult initially to distinguish subcycle motions from primary motions. Subcycle frequencies are important since they are greater than the fundamental frequency and represent greater repetition than revealed by the fundamental frequency alone. The electrogoniometric method is capable of resolving small changes in angles automatically with consistency and precision. A statistically significant difference was observed between the different job conditions as supported by the ANOVA statistics.

The operator performing the press operation moved the hands from the press activation buttons to a fixture, released the finished part, placed a new part in the fixture, and returned to the press activation buttons. This overall motion (button-to-button cycle) defined the fundamental cycle. The release of the finished part was performed with a quick extend-flex motion that produced the subcycle motion. A separate time study had to be performed for each joint in order to quantify these subcycle frequencies. Spectral analysis automatically provided the same information as time-and-motion study and the posture classification analysis. In all cases, spectral analysis results had better frequency and amplitude resolution.

Repetition frequencies for specific work elements were quantified using time study by assigning the appropriate breakpoints. Use of an interactive computer and VCR off-line for breakpoint assignment facilitated fundamental and subcycle repetition frequency identification (Radwin and Yen 1993, Yen and Radwin 1995). Marras and Schoenmarklin (1993) segmented motions into cycles in the field using the analyst's visual judgement as the posture data were being recorded. The analyst pressed a button that synchronized the data with the event. The accuracy of synchronization was dependent on the vigilance and reaction time of the observer. The spectral analysis method is robust and not dependent on such procedures.

Time-and-motion study repetition frequency was strongly correlated with the spectral analysis repetition frequency. The high correlation of 0.97, a regression slope near unity, and the lack of statistical differences between the repetition frequency values obtained for spectral analysis and time-and-motion study, provided strong support that both analysis methods are equivalent estimators of repetition. Furthermore spectral analysis indicated the fundamental and subcycle frequencies for each joint in a single analysis where time study required a separate analysis for each subcycle frequency.

Detailed epidemiological studies for identifying doseresponse relationships to physical stress have previously been limited by the method used for dose quantification. In many epidemiological studies reported in the literature, the exposure factors are quantified in terms of discrete high/low levels (Winkel and Westgaard 1992). A more precise method is needed to provide a greater level of detail. Spectral analysis provides more resolution than posture classification and is more convenient to perform than time-and-motion study, and can potentially facilitate large-scale studies.

Posture classification provided a much coarser measure of joint motion than electrogoniometer spectrum. The electrogoniometer data had a sample rate of 60 Hz with 256 amplitude levels compared with a 3 Hz sample rate and at most six amplitude levels for posture classification. This resolution difference produced poor correlations between posture classification and electrogoniometric spectral analysis. Only when joint motion was sufficiently greater than the posture classification angle partition resolution did electrogoniometer spectrum correlate better with posture classification. The lack of correlation was, therefore, due to the limitations of posture classification and not direct posture measurements.

The electrogoniometers had a 1° precision and a $5-7^\circ$ accuracy. Accuracy is the difference between the quantity as measured and its true value. Precision is the ability of an instrument to reproduce the same measurement over and over again. The instrument design and calibration affect accuracy. Precision is affected by the resolution of the measurement. An instrument can simultaneously have high precision and poor accuracy. The posture classification precision in this study was $\pm 22.5^\circ$ at best. Much of the joint angle magnitude information was lost when angles were reduced into a single angle, particularly when joint motions were small. The posture classification time series data only indicated motion when the joint angles exceeded angle partitions. Joint motions within the angle resolution were incorrectly considered static. Posture classification also contained analyst error caused by poor visual contrast, parallax error and field of view. Although the electrogoniometer data has notable error, it is considered to be markedly less than posture classification, and sufficient accuracy for the current study.

There were no statistically significant differences observed between the spectral analysis and posture classification results for sustained posture. The mean absolute difference of 15.31° for sustained posture was 11% full range error for wrist flexion/extension (150°) and 7% full range error for shoulder flexion/extension (240°). Ericson *et al.* (1991) observed 10 – 13 errors in visual joint estimations. Using the electrogoniometer data as the reference, the mean absolute differences between analysis methods for sustained posture were similar to those finding. The magnitude of the differences between the different analysis methods for different joints and jobs were not remarkable. The regression slopes between spectral analysis and posture classification for sustained posture reveal that both analysis methods agree, with posture classification over-estimating spectral results by $<10\%$ for sustained posture.

A significant difference in RMS deviation was observed between analysis methods. The mean RMS deviation was 9.78° for spectral analysis and 14.23° for posture classification. The tendency for posture classification to over-estimate RMS deviation when compared with electrogoniometric data was supported by the linear regression slope of 0.65 as well as the significant difference between the two analysis methods. Genaidy *et al.* (1993) reported that observers tended to over-estimate shoulder joint motion when the actual motions were between 1 and 60° supporting the findings of the current study. The accuracy of the joint angle estimates are dependent on the quality of the observer view and subject orientation, which can be the main source of error for posture classification. Joint motions less than the angle partitions were incorrectly classified as sustained postures when using posture classification. Consequently repetitive motions less than the angle resolution were missed using posture classification. Sustained posture correlated better than RMS deviation between spectral analysis and posture classification.

The forearm rotation data recorded was unusable for all jobs except the construction vehicle operation. Forearm rotation was measured using a torsional strain gage electrogoniometer attached along the ulnar bone with one end near the lateral epicondyle and the other end near the wrist. As the forearm rotated, a small angular difference was measured between the two electrogoniometer ends. A large amplifier gain was necessary to achieve a usable output voltage. The forearm rotation voltage output saturation occurred frequently during movement. Skin surface tightness also influenced the measurable differences between the electrogoniometer ends. Loose skin produced very poor rotation data and inconsistent angle calibration, which was the primary cause for unusable data. An electrogoniometer capable of measuring forearm rotation must have sufficient angle resolution to detect the small angular difference between the elbow and wrist locations as well as overcome the sliding of the sensor ends on the skin while maintaining a small and low mounted profile. Forearm rotation is also subject to many of the limitations discussed for posture classification, particularly observer position and view.

Much of the error associated with spectral analysis results came from the accuracy of the sensors and their calibration. Moore *et al.* (1991) observed errors up to 11% due to crosstalk in the strain gage wires of the Penny and Giles bi-axial sensors. Hansson *et al.* (1996) observed wrist angle measurement errors for the bi-axial electrogoniometers due to crosstalk caused by forearm rotation. Wrist angle crosstalk error of up to 26% was observed for ±30° forearm rotation (Hansson *et al.* 1996). Careful calibration protocol can help to reduce the overall posture errors.

Ultimately, better posture sensors for field studies that provide less error are desirable and anticipated in the future. The spectral analysis method should satisfy the need to conveniently reduce continuously measured data into useable metrics.

5. Conclusions

Spectral analysis when applied to continuously recorded posture data from repetitive industrial work was capable of resolving differences in repetitiveness, RMS deviation, and sustained posture. Spectral analysis of electrogoniometric data resulted in repetition frequencies that were highly correlated (0.97) with time study analysis and agreed with the time study results with $< 5\%$ error. Spectral analysis also revealed subcycle frequencies that were often difficult to identify from visual observation.

Since posture classification was very limited in resolution and often contained errors caused by poor joint visibility, the correlation between the postural classification and spectral analysis for sustained posture was 0.77, and for posture deviation was 0.53. When considering only larger motions that exceeded the posture classification angle resolution, the correlation between postural classification and spectral analysis for sustained posture and posture deviation was 0.81.

In most cases, posture classification best represented the motion when there were large joint deviations or extreme postures. Posture classification only provided a coarse representation of the actual motions with the magnitude resolution having a maximum of six levels and the time resolution of three samples per s. The poor time and magnitude resolution of posture classification tends to classify small motions as sustained postures.

Both analysis methods produced similar results with no statistically significant differences between them when the range of motion was sufficiently great. However, the mean differences between the analysis methods were affected by posture classification resolution. Spectral analysis agreed with posture classification even with poor correlation with a $< 10\%$ difference.

This study showed that spectral analysis of electrogoniometer data were a useful method for analyzing repetitive manual work providing results on the RMS joint deviations, sustained postures, and repetition frequencies. Furthermore direct measurement results were more precise than observational analysis. In this study, posture data were used to demonstrate the usefulness of spectral analysis, however other biomechanical data (force, EMG, velocity, acceleration) should be suited for analysis in a similar manner.

Acknowledgments

This research was sponsored by Grant no. DMII-9158136 from the National Science Foundation and by matching gifts from industry. The authors thank the manufacturing plants and companies that participated in this study.

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