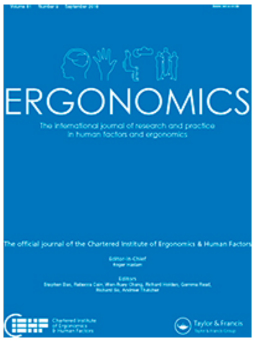

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Use of accelerometers as an ergonomic assessment method for arm acceleration—a large-scale field trial

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Ergonomists need easy-to-use, quantitative job evaluation methods to assess risk factors for upper extremity work-related musculoskeletal disorders in field-based epidemiology studies. One device that may provide an objective measure of exposure to arm acceleration is a wrist-worn accelerometer or activity monitor. A field trial was conducted to evaluate the performance of a single-axis accelerometer using an industrial population (n= 158) known to have diverse upper limb motion characteristics. The second phase of the field trial involved an examination of the relationship between more traditional observation-based ergonomic exposure measures and the monitor output among a group of assembly-line production employees (n= 48) performing work tasks with highly stereotypic upper limb motion patterns. As expected, the linear acceleration data obtained from the activity monitor showed statistically significant differences between three occupational groups known observationally to have different upper limb motion requirements. Among the assembly-line production employees who performed different short-cycle assembly work tasks, statistically significant differences were also observed. Several observation-based ergonomic exposure measures were found to explain differences in the acceleration measure among the production employees who performed different jobs: hand and arm motion speed, use of the hand as a hammer, and, negatively, resisting forearm rotation from the torque of a power tool. The activity monitors were found to be easy to use and non-intrusive, and to be able to distinguish arm acceleration among groups with diverse upper limb motion characteristics as well as between different assembly job tasks where arm monitors were performed repeatedly at a fixed rate.

1. Introduction

Methods to reliably quantify exposure to biomechanical stress in large-scale field studies are needed to permit evaluations of dose-response relationships. Pathophysiologic mechanisms in the development of work-related musculoskeletal disorders (WMSDs) are poorly understood, but are hypothesized to result from repetitive or sustained microtrauma (mechanical or physiologic) that compromise the integrity or functioning of specific tissues and structures of the musculoskeletal system over time (Goldstein *et al.* 1987, Armstrong *et al.* 1993). Moore and Wells (1992) describe

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repetitive motion as a complex factor in the development of chronic musculoskeletal disorders because it has several component characteristics: the range of motion at a joint (postural dynamics); how rapidly motions are performed; how often similar movements are performed; and how many similar movements are performed per day. Data obtained from accelerometers are conceptually related to these components of dynamic motion or 'repetitiveness', but this relationship must be substantiated empirically.

Use of instrumentation to assess ergonomic exposures, such as electromyography, electrogoniometers and inclinometers remains limited largely to laboratory research settings or small-scale field studies. In recent years, there has been increased use of accelerometers in laboratory and field settings for quantifying human motion in research ranging from circadian patterns, hand tremor, and physical activity (as a surrogate measure of energy expenditure) (Brooke *et al.* 1985, Balogun *et al.* 1986, Caldwell and Cornum 1992).

Accelerometers have also been used by ergonomists to quantify motion patterns among worker populations who may be at risk for developing WMSDs. Bhattacharya *et al* (1985) have used accelerometry to determine biomechanical forces by measuring the impact deceleration of a carpet layer's knee while using a knee kicker during carpet laying. Grant *et al* (1995) used accelerometers to compare the amount of upper limb and leg activity of supermarket cashiers with that of supermarket stock clerks. As expected, supermarket cashiers had less frequent leg accelerations and more frequent upper limb accelerations. Andersson *et al* (1996) have performed a pilot investigation of accelerometers to measure movement patterns during ordinary industrial work. They used three accelerometers (perpendicular to one another) attached at the wrist.

Accelerometers have the advantages of being relatively low cost, requiring little on-site preparation for data collection, being able to be used in an unobtrusive manner, and producing an objective measure of exposure that is plausibly an important marker for musculoskeletal strain. More information was needed about their performance in a field survey before making a commitment to use them in a large-scale epidemiologic study.

A two-phase field trial was conducted to investigate the use of single-axis accelerometers in assessing arm acceleration in an industrial population.

The specific aims of the research were as follows:

(1) to determine if the accelerometer can distinguish arm acceleration among three diverse occupational groups;
(2) to determine if the accelerometer can distinguish arm acceleration among employees assigned to line-paced production assembly work; and
(3) to determine what ergonomic characteristics of the production work tasks are associated with increased arm acceleration.

2. Instrumentation

The activity monitors used in this study were Model 7164, Versions 1.0 and 1.1 (Computer Science and Applications Inc, Shalimar, FL; 1996); (figure 1). Each activity monitor weighed 42.6 g and its dimensions were 5.1 ×3.8 ×1.5 cm. The monitor's plastic casing had two 'belt loops', enabling a velcro strap to be used to secure the instrument to the back of the wrist. Each activity monitor contained one

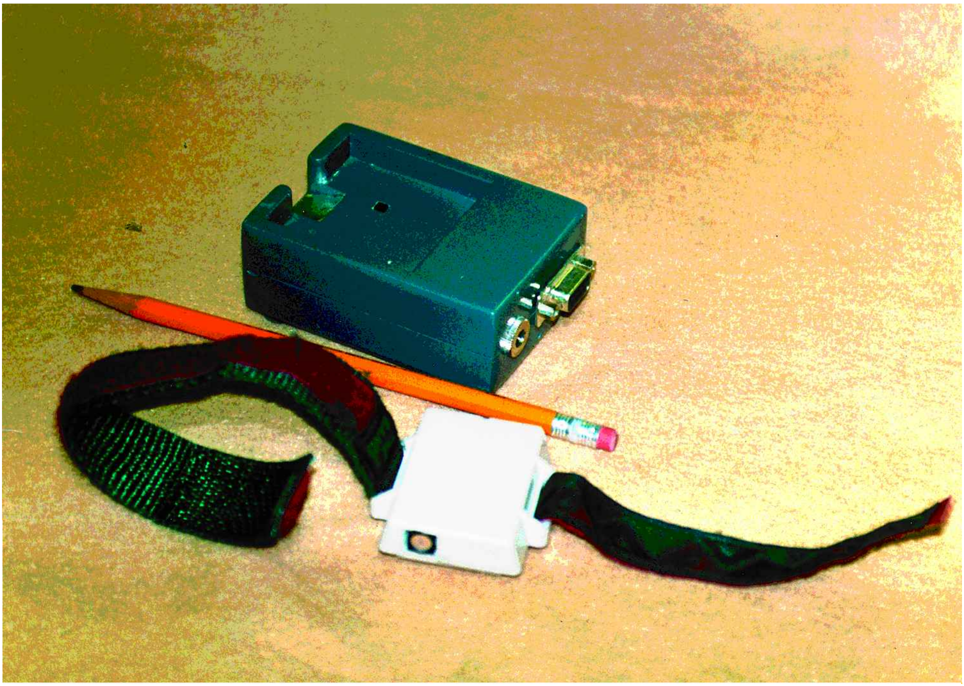

Figure 1. Wrist activity monitor Model 7164, Version 1.1 (foreground) and reader interface unit (background).

accelerometer and thus measured motion in one plane or axis. When attached to a person's wrist, it measured acceleration parallel to the long bones of the forearm. Redmond and Hegge (1985) found that a single-axis accelerometer produced a fair index of the other two axes ($R^2 = 0.60 - 0.98$) when studying 30 soldiers on a training exercise. A reader interface unit is used to transmit data between a computer and the activity monitor. Thus no external cords or 'tethering' of the instrument are required during set-up, data collection, or when downloading data to a computer.

Unlike acceleration data used in ergonomic studies by Marras and Schoenmarklin (1991) that computed *angular* acceleration with reference to articulating limb joints, the instruments used in this study measured *linear* acceleration. This use of instruments measuring linear acceleration as opposed to computing angular acceleration was due to considerations of equipment availability and suitability for use in a field survey. It is not known at this time if one of these two types of motion acceleration measures is superior as a marker of strain on the musculoskeletal system.

The A/D converter has 8 bits or 256 (2^8) levels, and the digitized output is stored in bits from 0 to 255. The accelerometer is designed to detect acceleration amplitudes from 0.05 to 2.13 g (0.49 to 20.89 m s^{-2}). Acceleration has positive and negative components so values 0 to 127 constitute negative acceleration, value 128 signifies no movement, and values 129 to 255 denote positive acceleration. Readings of 0 (negative acceleration) and 255 (positive acceleration) are equivalent to -2.13 and 2.13 g, respectively. Greater positive or negative accelerations are recorded as these maximum values.

The frequency of the acceleration cannot be determined from the digitized output. The instrument records the amplitude, but not the frequency. The amplitude can be reduced by the passband filter depending on frequency. The filter is most transparent at the frequency of 0.75 Hz. For frequencies below 0.21 Hz and above 2.28 Hz, the amplitude is reduced to 50% of the magnitude. These frequencies are similar to those chosen by Redmond and Hegge (1985; 0.25 Hz and 2.0 Hz) to eliminate external vibration and to minimize baseline shift from wrist rotation while still showing wrist movement.

Accelerometers used in this study were designed to sample at a rate of 10 Hz. Summed mode (§2.1.) provided an output for each 1-s sampling period. The Version 1.1 monitors collected the data in raw data mode providing an output for each 1/10 s reading. Calibration was performed by the equipment supplier prior to the data collection survey. No on-site (field) calibration is required. Details of the monitor calibration procedure are reported elsewhere (Tryon and Williams 1996).

2.1. *Summed mode*

The instrument signal can be processed using the summed magnitude algorithm. In this processing mode, the magnitude of acceleration is accumulated over a pre-specified time sampling period or epoch. An epoch can be defined by the user during the initialization process. For this study, when using the summed mode, the epoch was set to 1 s (the smallest sampling period available for activity monitor Version 1.0). Therefore, since the monitor collects data at 10 Hz, 10 raw data points were added together (*or summed*) for each 1-s epoch. The 10 raw data points are summed by the monitor's microcontroller, and the one resulting number is reported for the 1-s period. The following formula is used:

$$\text{Count} = \sum_{i=1}^{10} |n_i - 128|,$$

where n_i= raw data, count is in bits s^{-1}.

The count is a *sum* and not an average, so the bigger the epoch period, the larger the count. The instrument does not report data in any customary units but can be converted to m s^{-2} by using the following formula:

$$\text{Acceleration}\left(\mathrm{m\ s^{-2}}\right) = \text{count} \times \frac{1}{10}(\mathrm{s}) \times \frac{2.13\ (g)}{128\ (\text{bits})} \times \frac{9.8\ (\mathrm{m\ s^{-2}})}{1\ (g)}$$

2.2. *Raw data mode*

Raw data mode gives the output in bits from 0 to 255. This information can be converted to m s^{-2} using the following formula:

$$\text{Acceleration}\left(\mathrm{m\ s^{-2}}\right) = |n_i - 128| \times \frac{2.13\ (g)}{128\ (\text{bits})} \times \frac{9.8\ (\mathrm{m\ s^{-2}})}{1\ (g)},$$

where n_i= raw data.

3. Study methods

This study was completed in two sequential phases: Phase I, to evaluate the performance of the activity monitors using an industrial population known to have diverse arm acceleration characteristics; and Phase II, to determine the relationship between observation-based exposure measures and the monitor output among similar line-paced production jobs.

For both phases of the study, the activity monitor was attached to the back of the wrist on the participant's dominant side. It was believed that most tasks, e.g. hand tool use, would be performed primarily with the participant's dominant hand. The monitor was attached so that movements parallel to the long bones of the forearm were most sensitive.

3.1. *Phase I methods*

In the first phase of the study, a convenience sample (with selection of participants by choosing those most readily available) of employees in three occupational groups was selected to participate in the study: hourly employees who worked on a traditional washer assembly line with fixed work cycles; hourly employees assigned to a new washer line during its start-up operations (i.e. work pace not governed by fixed cycle times); and salaried employees (managers, technical support, clerical staff, etc). Some of the salaried employees were 'heavy' computer users (using a computer for 4 h or more per day). During Phase I, 19 activity monitors (Version 1.0) were used in the summed data mode with a 1-s epoch. Each participant wore the monitor for a minimum of 1 h during one work shift. At least 5 min of video recordings were obtained for each participant to provide a visual frame of reference for the monitor data.

For all workstations on the traditional washer assembly line assembly tasks were performed at a fixed rate with a 22-s cycle in accordance with the speed of the conveyorized assembly line during two work shifts. Employees on both work shifts were sampled; operating conditions were similar on the first and second shift. Within these short cycle time job assignments, task content was small. With few exceptions, each employee on the assembly line during each shift worked at a single workstation and performed one of several different assembly tasks. Example job assignments on the assembly line included clamping the hose to the tub, installing the tub bolts, installing the spin tub to the trunnion, etc. Many jobs involved fastening lightweight parts using clamps or screws. Pneumatic hand tools were used by about one-third of the employees.

In contrast, employees on the new washer line performed odd jobs consistent with pre-production 'start-up' operations (ordering parts, determining future tooling and equipment needs, testing hole sizes for quality, cleaning, etc.). As such, hourly employees assigned to the new washer line were not involved in fixed-pace, short-cycle assembly tasks.

For each participant, 1 h of data collection (less a 10 min break) resulted in 3000 data points. An arithmetic mean was computed from the 3000 data points yielding one dependent variable, arm acceleration, for each participant. The arm acceleration data for the three employee groups were compared to each other in pairs. A t-test was used to compare the new washer line employees to the salaried employees. A modified t-test called a t prime test (t'-test) was used for comparisons involving the traditional washer line because the variance in this group was unequal to (greater than) the variance found in the other two occupational groups (Steel and Torre 1980). Following each comparison, the p-values were multiplied by three for a Bonferroni *post hoc* comparison (Keppel 1991). The t-tests were also used to compare first shift to second shift jobs on the traditional washer line and, for the salaried group, these 'heavy' computer users were compared to all others. A one-way ANOVA was used for the between-job comparison of the variable arm acceleration.

3.2. *Phase II methods*

During Phase II, a new data collection period was initiated involving only employees assigned to the traditional washer line. Since the Phase I study, second shift operations had been discontinued and cycle time had been reduced to 17 s. Data from the Phase I study in which two or more employees worked at the same job were used to determine the variance for participants and jobs for the purpose of a power analysis. Thirty activity monitors (Version 1.1) were used in raw data mode during Phase II.

An ergonomic risk factor checklist was completed by an ergonomist during an observational assessment of all jobs (appendix 1). The following exposure conditions were used for this study: peak shoulder flexion, peak shoulder extension, peak shoulder abduction, unsupported arms, forearm pronation and supination, rapid rotation of the forearm, resisting forearm rotation from a power tool, peak wrist flexion, peak wrist extension, wrist radial deviation, wrist ulnar deviation, use of the hand as a hammer, cycle time, and recovery time between cycles (idle time spent waiting for the next washer). The most extreme postures observed during the work cycle were reported. In addition to the ergonomic risk factor checklist, a workstation profile worksheet was administered by a technician and recorded, among other things, use of a power tool and number of power tool activations per cycle.

A visual-analogue scale for rating repetition of hand and arm activity was developed and validated at the University of Michigan (Latko *et al.* 1997) and was adapted for use in this study (appendix 1). The scale format was maintained in the adaption so that it remained a 0–10 visual analogue rating scale. The adaption involved the creation of two scales, which were derived from the separation of the verbal anchor terms concerning hand and arm motion speed from the terms concerning the length and frequency of pauses between hand exertions. This adaptation was made following earlier experiences with the recommended format of the scale in a large field study, where raters experienced difficulties integrating into a single score the component of exposure pertaining to hand motion speed and the component pertaining to pauses between exertions. While the adoption of the recommended multi-rater consensus-based exposure assessment would have assisted in rating determinations, resource limitations made this approach infeasible. Validation of these adapted rating scales will need to be performed in future work.

Production flow bottlenecks, relating primarily to line-balance problems, were somewhat common among assembly operations on the traditional washer line, therefore an attempt was made to sample all participants for one full hour on four consecutive work days. However, numerous operating conditions, such as absence from work of some participants, job rotation, and instrument error made this sample plan impractical; at the conclusion of the field survey, only 25 participants had 1-h files for all 4 days and a further five participants had data for 3 days. After eliminating data files that did not satisfy the 50-min (1 h, less a 10 min break) continuous sampling criteria (i.e. shorter files were obtained mainly due to job rotation), two 1-h samples were available for 48 participants. To improve the uniformity of the data across participants, the first two 50-min samples obtained for each participant were used.

4. Study results

Table 1 shows demographics for both phases of the study. Phase I activity monitor data were collected from a total of 158 employees as follows: 82 of 117 (70%) traditional washer line employees; 13 of 17 (76%) new washer line employees; and 63 of 218 (29%) salaried employees. During Phase II, monitor data were collected from 62 of 79 (78%) traditional washer line employees. However, data from only 48 of the participants were used for analyses as described in §3.2.

Three data files from Phase I and 22 files from Phase II were unusable because of data quality problems related to apparent computer or instrument errors. These data were removed prior to analysis.

4.1. *Phase I results*

Arm acceleration data for each employee group in Phase I are shown in table 2. These results showed that traditional washer line employees had higher arm acceleration than the new washer line employees (t'-test, df= 30, $p \leqslant 0.001$) and the salaried employees (t'-test, df= 135, $p < 0.001$). Futhermore, the arm acceleration of

Table 1. Participant demographics during each phase of the field trial by employee group.

Employee group	% Left-handed	% Male	Job duration, years (SD)	Age, years (SD)
Phase I (n= 158)				
Traditional washer line (n= 82)	13	50	2.4 (2.4)	38.3 (9.9)
New washer line (n= 13)	15	54	0.5 (0.4)	38.7 (5.5)
Salaried employees, total (n= 63)*	11	60	5.6 (5.9)	42.7 (9.7)
Salaried employees, VDT users (n= 15)†	7	27	6.7 (6.4)	42.4 (11.3)
Salaried employees, other (n= 48)	13	70	5.2 (5.8)	42.8 (9.3)
Phase II (n= 48)				
Traditional washer line	13	45	2.8 (4.1)	42.2 (9.9)

*Clerks or secretaries (9%), supervisors (18%), managers (17%), professionals (16%), technical support personal (engineers, draftsmen, or laboratory technicians 40%).

†VDT users' group consisted of salaried employees who reported daily computer use of 4 h or more; this group comprised employees with various job classifications (e.g. clerks, engineers).

Table 2. Phase I study—summary of arm acceleration parameters by employment group.

Employment group*	Number of participants	Arm acceleration (bit s^{-1}) [m s^{-2}]	Standard deviation	Range arm acceleration (bit s^{-1}) [m s^{-2}]
Traditional line	82	73.2 [1.20]	25.4	19.8–165.1 [0.32–2.70]
New line	13	48.9 [0.80]	12.8	30.0–70.7 [0.49–1.54]
Salaried employees	63	26.1 [0.43]	14.9	5.5–96.7 [0.09–1.58]

*Bonferroni *post hoc* analysis showed that the arm accelerations among pairs of employment groups were statistically different from each other ($p \leqslant 0.001$).

the new washer line employees was found to be higher than that of the salaried employees (t-test, df= 74, $p < 0.001$).

Of the 63 salaried employees who wore an activity monitor, 15 identified themselves as heavy computer users. No statistically significant difference was found in arm acceleration using a t-test between the heavy computer users and the other salaried employees (df= 61, $p = 0.42$) (table 3).

There was no significant difference in arm acceleration between first and second shifts of the washer line (t-test, df= 80, $p = 0.44$). There were 26 workstations on the traditional washer line with data from at least two employees (one per shift). Using the arm acceleration data from these 26 workstations, a between-workstation analysis of variance was performed using an F-test, and the differences in arm acceleration were not statistically significant (df= 25 and 32, $p = 0.13$).

4.2. *Phase II results*

Table 4 shows some descriptive arm exposure information for the 48 jobs that were evaluated. All files used in the analysis contained 50 min of data (1 h, less a 10-min break), which resulted in 30 000 data points per file. Two files were used for each of the 48 workers giving a total of 96 files. An arithmetic mean was computed from the 30 000 data points for each file yielding the dependent variable, arm acceleration. A general linear model (SAS Institute, 1990) was used to test if the independent variable workstation (48 levels) was associated with arm acceleration. The variability between the two files for each subject performing the same job forms the denominator for the general linear model. Arm acceleration was significantly different between jobs ($p \leqslant 0.0001$). The two arithmetic means for each participant were then averaged, yielding one value for the dependent variable, arm acceleration, for each participant. These data were then merged with the risk factor checklist data by workstation.

General linear models (SAS Institute 1990) were developed separately for each ergonomic risk factor checklist measure to determine which exposure variables were significantly associated with the dependent variable, arm acceleration. The following risk factor checklist variables were *not* significantly related to arm acceleration ($p > 0.10$): recovery time; shoulder extension; shoulder flexion; wrist flexion; wrist extension; wrist radial deviation; forearm pronation and supination; rapid rotation of forearm; unsupported arm; cycle time; and number of power tool activations per cycle. Table 5 (categorical exposure variables) and Figure 2 (continuous exposure variables) show the significance levels of the checklist measures that were found to be

Table 3. Phase I study — summary of arm acceleration by computer use among salaried employees.

Computer use*	Number of participants	Arm acceleration (bit s^{-1}) [m s^{-2}]	Standard deviation	Range arm acceleration (bit s^{-1}) [m s^{-2}]
< 4 h/day	48	25.2 [0.41]	15.3	5.5–96.7 [0.09–1.58]
⩾4 h/day	15	28.8 [0.47]	13.8	13.2–71.9 [0.22–1.17]

*Comparison between the two levels of computer use was statistically non-significant, $p = 0.42$.

Table 4. Phase II study—arm exposure information for 48 workstations on the traditional washer line.

Information	Number exposed	Proportion exposed (%)
Shoulder extension, $x > 15°$	17	35.4
Shoulder abduction, $30° < x < 60°$	20	41.7
Shoulder abduction, $x > 60°$	25	52.1
Shoulder flexion, $45° < x < 90°$	35	72.9
Shoulder flexion, $x > 90°$	6	12.5
Forearm pronation	48	100.0
Forearm supination	34	70.8
Resisting forearm rotation from a power tool*	9	18.8
Wrist extension	39	81.3
Wrist flexion $20° < x < 45°$	26	54.2
Wrist flexion $x > 45°$	8	16.7
Wrist radial	29	60.4
Wrist ulnar	41	85.4
Use of the hand as a hammer	2	4.2
Power tool use	16	33.3

*Resisting forearm rotation from a power tool, was marked positively if an observer indicated that a power tool caused the employee to resist rotation when the power tool reached full torque.

Table 5. Phase II study—significance of general linear models developed separately for each ergonomic risk factor checklist measure and arm acceleration by exposure level.

Independent variable	Number exposed	Arm acceleration (bits s^{-1})	Arm acceleration [m s^{-2}]	p value
Shoulder abduction, $0° < x < 30°$	3	6.55	1.07	
Shoulder abduction, $30° < x < 60°$	20	7.65	1.25	0.05
Shoulder abduction, $x > 60°$	25	9.35	1.53	
Wrist ulnar				
Yes	41	8.83	1.44	0.02
No	7	6.36	1.04	
Use of the hand as a hammer				
Yes	2	14.31	2.34	
No	46	8.22	1.34	0.01
Resisting forearm rotation from a power tool				
Yes	9	6.55	1.07	
No	39	8.91	1.46	0.02
Power tool use				
Yes	16	7.09	1.16	0.01
No	32	9.16	1.50	

statistically significant for each general linear model, as well as arm acceleration by exposure level, illustrating directional influence.

These checklist measures that were significant (general linear model) at the level $p \leqslant 0.10$ were selected for entry into a multivariate general linear model. To identify potential colinearity problems, correlation coefficients for all continuous variables were reviewed to determine if any two variables were too closely correlated, and

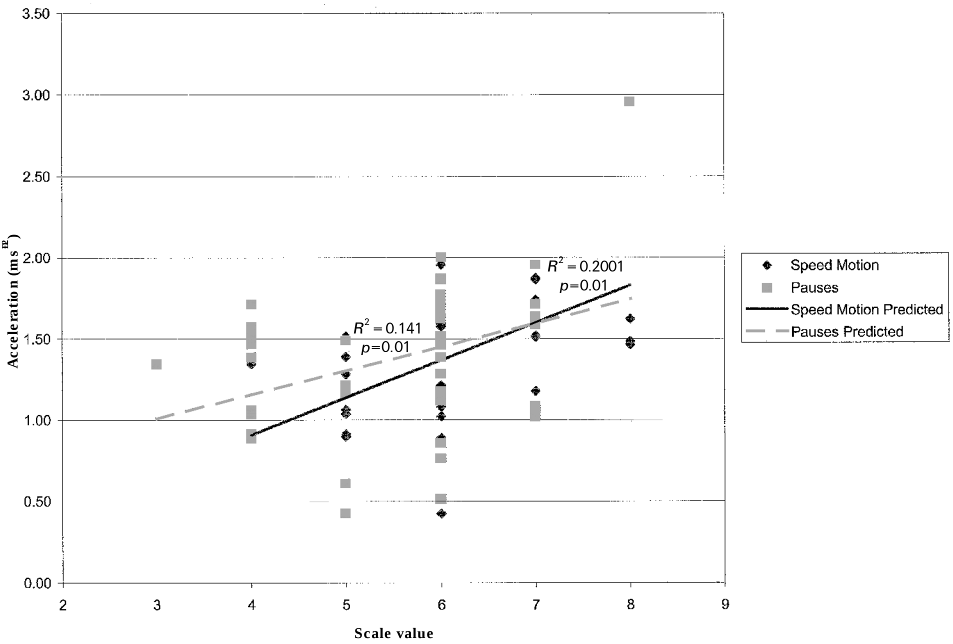

Figure 2. Significance of ergonomic risk factor checklist measures speed of hand and arm motion and pauses between hand exertions using separate general linear models.

none were. Percentage agreement was calculated for categorical variables to determine if any were too closely related. Since there was high concordance between power tool use and resisting forearm rotation from a power tool, as evidenced by a moderately high κ value (0.63), those variables were not entered into the same model.

Two continuous and five categorical variables were used as independent variables in a general linear model. Those variables were: hand and arm motion speed; use of the hand as a hammer; resisting forearm rotation from a power tool; shoulder abduction; wrist ulnar deviation; pauses between hand exertions; and use of a power tool (although use of a power tool and resisting forearm rotation from a power tool were not both used in the same model). Starting with a full model, variables were removed one at a time (largest *p*-value first) until each remaining variable had a significance level of 0.05 or less. The following variables remained in the model: hand arm motion speed; use of the hand as a hammer; and resisting forearm rotation from the torque of a power tool ($R^2 = 0.430$). Table 6 shows the coefficients, semipartial R^2, and p value for the general linear model. When power tool use was used in place of resisting forearm rotation from a power tool, similar results were obtained ($R^2 = 0.415$).

5. Discussion

The Phase I results showed that the activity monitors could distinguish arm acceleration between groups with diverse upper limb motion requirements. Work on the traditional washer assembly line was very hand intensive and routinized compared to the work of hourly employees performing ‘start-up’ non-production operations and the work of salaried employees. The ability of these activity monitors

Table 6. Coefficients and semipartial R^2 from the general linear model ($R^2 = 0.430$).

Variable	β	Semipartial R^2	p value
Speed of hand and arm motion	1.20	0.136	0.0003
Use of the hand as a hammer	4.50	0.080	0.0070
Resisting forearm rotation from a power tool*	−2.20	0.076	0.0033

*When use of powertool was placed in the model instead of resisting forearm rotation from a power tool, results were similar: $\beta = -1.70$, Semipartial $R^2 = 0.062$, $p = 0.0144$, and $R^2 = 0.415$.

to distinguish between work groups known observationally to have very different upper limb motion requirements was an important first step in determining the utility of these monitors in quantifying exposure to arm acceleration.

The Phase II survey was aimed at comparing the similarly paced jobs on the traditional washer assembly line. Although all employees repeated their tasks about every 17 s in accordance with conveyor line speed, task content varied and the speed of hand and arm motion was observed to vary between workstations. The activity monitor was able to detect differences in arm acceleration at these different workstations.

In separate general linear models, a statistically significant association with arm acceleration was found for seven checklist measures of the assembly work tasks that were determined by trained observers. In multivariate analyses, three of the seven ergonomic characteristics were found to be significant and explained 43% of the variability in arm acceleration. These variables were hand and arm motion speed, use of the hand as a hammer, and negatively, resisting forearm rotation from the torque of a power tool.

Higher measures of hand and arm motion speed determined from observer's ratings on a 0–10 visual-analogue rating scale (appendix 1) were found to be correlated with higher acceleration readings from the activity monitor. Similarly, in separate general linear models, the 0–10 visual-analogue rating scale for pauses between hand exertions showed that when no regular pauses were present, higher acceleration readings were obtained. The activity monitors distinguished between the hand and arm motion speed requirements of similarly-paced production assembly work tasks, suggesting that the activity monitor provides a sensitive measure of the dynamic motion of the upper limb.

When a workstation required an employee to use his hand as a hammer, greater arm acceleration resulted. The act of using the hand as a hammer may cause very high deceleration rates over a short period of time because the hand in motion stops abruptly. Although this may not be a traditional measure of repetition, it may be a valuable measure for ergonomic investigations. This activity has previously been shown to be a risk factor for musculoskeletal disorders of the upper limb (Kendall 1960). Hence, these high decelerations may be useful indicators of musculoskeletal strain and should not be filtered out.

Resisting forearm rotation from a power tool was a factor that *reduced* the level of arm acceleration. The activity monitor has been designed to dampen the high frequencies caused by vibration of power tools, so this result suggests that the low-pass filter that reduces signals above 2.28 Hz to magnitude functioned properly. The reduced arm acceleration from those subjects who used a power tool is believed to be due to the postural fixity of the wrist during power tool use. Observations of study participants who used power tools to install fasteners during assembly line tasks confirmed that precise movements and static loading of the hand and arm were generally required.

Since hand and arm motion speed, use of the hand as a hammer, and resisting forearm rotation from a power tool (negatively) are significant predictors of arm acceleration, the activity monitor appears to provide a useful measure of dynamic arm motion in industrial work tasks. High repetition has been shown to be a risk factor for many musculoskeletal disorders (Silverstein *et al.* 1987, Bernard 1997). Further work is needed to investigate the relationship between arm acceleration and musculoskeletal disorders.

6. Instrument limitations

While the data from this field trial have been encouraging, it is important to note the limitations of this instrument. The activity monitor is like a 'black box': there are no displays or indicator lights to determine when or what it is recording. Thus co-ordination is required between initialization (which may be performed for a batch of monitors at a time) and the distribution of the activity monitors to employees. Simultaneous video recordings are important for obtaining a visual frame of reference and, to some extent, can aid in judgements regarding data quality (e.g. when a long data string of zeros is found). An event marker is now available on newer models, which may reduce the need for field staff to record the start and stop time of scheduled and unscheduled work breaks manually.

Twenty-five data files (8% of those collected) were found to have data quality problems (e.g. the instrument was initialized for the wrong time, no movement was recorded, etc.). These data quality problems were not detected until after each of the field surveys was completed. It is therefore suggested that routine data quality checks be performed during the data collection effort to minimize data loss.

It is possible that this activity monitor will detect motion not directly associated with dynamic arm acceleration. If, for example, an employee were to jump or to have dynamic trunk motion when the arms were otherwise posturally fixed, the instrument would still record movement. The instrument may also detect sympathetic motion, or involuntary tremors, that may be mistaken for gross limb motion.

As for other instrumentation used in ergonomic studies, the activity monitor measure is body location specific and appears to provide data on only one characteristic of exposure: dynamic motion. By itself, the activity monitor data would not provide an adequate assessment of all potential ergonomic hazards of a job, but it could be used in conjunction with other exposure assessment methods to more fully quantify biomechanical load. The activity monitor may not be well suited for ergonomic studies involving work groups with more posturally fixed static muscle loading conditions as found in computer work.

7. Conclusions

A field trial was performed to examine the utility of accelerometers in providing a quantitative assessment of arm acceleration. A total of 43% of the variability in arm acceleration was explained by three observed ergonomic conditions that relate to the dynamic motion requirements of work: hand and arm motion speed; use of the hand as a hammer; and, negatively, resisting forearm rotation from the torque of a power tool.

The activity monitors were found to be easy to use in a field research setting for a large number of participants. No on-site calibration of equipment was required and field staff training requirements were minimal. Initialization or set-up of the instruments could be performed in less than 1 min per instrument. The procedure for downloading data files was simple, and the downloading time, which varied in relation to sampling mode and total sampling time, was not excessive. No participant complaints were obtained regarding instrument interference with job performance. In the Phase I study, 19 monitors were available to a two-person field team. At the conclusion of the second week, data had been collected on 158 employees with a minimum 1 h sampling time.

Summed data mode, using during Phase I, had the advantage of a longer maximum available recording time (over 9 h compared to less than 2 h) than the raw data mode used in Phase II. Raw data mode has the advantage of showing acceleration peaks because the recorded results are not summed. The total sampling period required will be an important practical consideration in determining which data mode to apply in future research efforts.

While the results of this field trial have been encouraging, future work is planned that will involve the use of spectral analysis of the activity monitor data to examine the relationship between the fundamental frequency and work cycle time. Radwin and Lin (1993) used spectral analysis of data from electrogoniometers to determine the repetitiveness of a laboratory task. They were able to view the frequencies of 0.2 and 0.4 Hz, which correspond to work pace.

Determination of the appropriate length of sampling time requires further investigation. The sampling period in Phase I of this study was limited to 50 min to accommodate sampling of a larger number of study participants. Shorter sampling times may not adequately capture the variability of exposure. During Phase II of the study, employees on the assembly line were sampled for at least 1 h on different days during one work week. Within-subject variability was evident between the sampling periods, even among those employees assigned to fixed-paced production operations. This variability is believed to be due to changes in line speed associated with production bottlenecks, which were not uncommon at this workplace. It is expected that the dynamic arm motion of non-routinized employees may be even more variable than was observed among the assembly employees. More research is needed to determine the appropriate length of sampling periods needed for both routinized and non-routinized work situations.

The activity monitor data in the two field trials was stored at 1 s and 1/10 s intervals, respectively, over a 50-min period, yielding a very dense continuous exposure measure. The metric computed and used for comparisons in this paper was a simple average. It is possible that a measure of central tendency will not adequately distinguish differences that are biologically meaningful in the development of work-related musculoskeletal disorders. Alternative metrics will be developed relating to threshold and variance effects. Once biologically meaningful metrics are developed, it will be important to examine the association between the monitor output (dynamic arm acceleration) and musculoskeletal disorders.

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Appendix 1. Risk factor checklist

Date ____________
1st SWC # ____________
2nd SWC# ____________
3rd SWC# ____________
Analyst ____________

Worker # (Y / N) ________
Team # ____________
Team # ____________
Team # ____________
Video Counter ____________
Time of Day ______ am/pm

Dept - Shift ______
Station # ______
Station # ______
Station # ______
Video Tape # ______

BODY LOCATION	DURATION OF EXPOSURE *(JOB ROTATION)*	POSTURE	EXTREME CATEGORY *(circle condition)*	ADDITIONAL FACTORS *(use empty space for notes)*
Back		Flexion	20°-45° / >45° / N	Y / N Prolonged sitting without adequate back support Y / N Feet not firmly supported while seated
		Extension	>20° / N	
		Twist	>20° / N	
		Lateral	>20° / N	
Neck		Flexion	20°-45° / >45° / N	
		Extension	>5° / N	
		Twist	≥20° / N	
		Lateral	≥20° / N	
Shoulder		Flexion	45°-90° / >90° / N	Y / N Unsupported arm (e.g., no arm rest when doing precision finger work)
		Extension	>15° / N	
		Abduction	30°-60° / >60° / N	
Forearm		Pronation	Y / N	Y / N Rapid rotation of the forearm Y / N Resisting arm rotation from a tool ✓✓ Y / N Extremely flexed elbow
		Supination	Y / N	
Wrist		Flexion	20°-45° / >45° / N	
		Extension	>30° / N	
		Ulnar	Y / N	
		Radial	Y / N	
Hand		Pinch	Y / N	Y / N Using hand as a hammer Y / N Gloves worn (____ fingers cut out?)
		Lateral pinch	Y / N	
		Hook	Y / N	
Fingers		Finger press	Y / N	Y / N Forceful finger gripping, e.g., click and drag a mouse Y / N Finger wrap worn
Lower extremity		Ankle	Y / N Rapid flexion or extension Y / N Use of foot control	Y / N Kneeling or squatting Y / N Stand on toes Y / N Use knee as a hammer or kicker

Cycle time *(production work only)* ________ seconds *(do not count rest time between cycles)*

Recovery time between cycles ________ seconds

Part of recovery time used to prepare for next cycle(s)? Y / N

Repetition ratings: for hands and arms only

0	2	4	6	8	10
Hands & arms idle most of the time	Hands & arms idle often	Slow motion of hands & arms	"Normal" motion of hands & arms	Rapid motion of hands & arms	Frenzied motion of hands & arms

0	2	4	6	8	10
Nearly continuous pause	Prolonged pause with occasional exertions	Frequent pauses ≥5 seconds between exertions	Consistent or regular short pauses between exertions	No regular pauses between exertions	Never a pause

EXPOSURE	DURATION OF EXPOSURE *(job rotation)*	CLARIFICATION	RESPONSE	ADDITIONAL FACTS
Repetition		Identical or similar upper extremity motions < 5 seconds apart	Y / N	
Control over work pace			Y / N	Y / N Active station box ✓✓ Y / N On main line Y / N Banks parts
Intensive keying		Similar to steady, paced data entry	Y / N	
Intermittent keying		Limited to <50% of work time	Y / N	
Contact stress		Hard, sharp objects pressing against skin	Y / N	Y / N Palm Y / N Elbow Y / N Fingers Y / N Armpit Y / N Wrist Y / N Leg Y / N Other__________
Segmental vibration		Affects a body part such as hand, arm	Y / N Tool	____ Other __________
Whole-body vibration		Affects whole body	Y / N	Source__________
Job rotation		Worker assigned to >one job	Y / N	Rotation Schedule: ______ times / day ______ times / week
Exposure to ergonomic hazards		Exposure to hazards on the job *(one job in the case of job rotation)*	Y / N	Duration Per Day: Y / N 7 hours 20 minutes _____ hours

✓✓ **Note exposure variations *(per model, etc.)* below:**

____

____

____

✓✓ **RECOMMENDATIONS: (incorporate worker's insights into recommendations)**

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