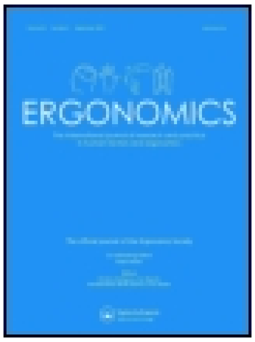

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Relationships between observational estimates and physical measurements of upper limb activity†

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This study examined the internal validity of observational-based ergonomic job analysis methods for assessing upper limb force exertion and repetitive motion. Six manual tasks were performed by multiple 'workers' while direct measurements were made to quantify force exertion and kinematics of the upper limb. Observational-based analyses of force and upper limb motion/repetition were conducted by 29 professional ergonomists. These analysts overestimated the magnitude of individual force exertions – temporal aspects of force exertion (duty cycle) were estimated more accurately. Estimates of the relative severity of repetitive motions among the jobs were accurate. Absolute counts of repetitive motions were less accurate. Modest correlations ($r^2 = 0.28$ to $r^2 = 0.50$) were observed between ratings of hand activity level and measured joint velocities. Ergonomic job analyses relying on systematic observation should be applied and interpreted with consideration given to the capabilities and limitations of analysts in estimating the physical risk factors. These findings are relevant to a better understanding of the internal validity of ergonomic job analysis methods based on systematic observation.

Keywords: repetition; force exertion; WMSD risk factors; upper limb

1. Introduction

Ergonomic assessments of upper limb intensive work typically include documentation of working posture, forcefulness of exertions and repetitive motion. Assessments of these physical risk factors are made with one or more of a variety of methods including self-report by workers, systematic observation by a job analyst and direct measurement with instrumentation-based sensors. Of these methods, exposure assessment by systematic observation may be the most commonplace. Observational-based methods are advantageous because they are more economical, involve fewer technical demands and yield more manageable data than instrumentation-based methods (Kilbom 1994). It is also believed that systematic observation by a trained analyst/ergonomist is generally more reliable than exposure documentation obtained by worker self-report. Since observational-based methods for ergonomic job analysis possess these benefits it is not surprising that so many methods have been developed and reported in the literature (e.g. Armstrong *et al.* 1982, Drury 1987, Stetson *et al.* 1991, McAtemney and Corlett 1993, Moore and Garg 1995, Occhipinti 1998, Seth *et al.* 1999).

While offering several advantages over instrumentation-based methods, observational-based methods are believed to sacrifice measurement validity. However, the degree to which these methods sacrifice validity over instrumentation-based methods has not been well established. The validity of observational-based methods for assessing working posture has been explored in several recent studies (Juul-Kristensen *et al.* 2001, Ketola *et al.* 2001, Paquet *et al.* 2001, Spielholz *et al.* 2001, Lowe 2004a,b, van Wyk *et al.* (in press)) by comparing analysts' observational estimates of working posture to direct measurements of corresponding joint angles. Fewer studies have investigated the validity of observational-based methods for assessing forcefulness of exertion and dynamic aspects of upper limb intensive work. This may be due largely to the fact that working posture of the upper limbs can be expressed clearly in terms of joint angles and thus a single measure can serve as a reliable reference standard of accuracy. A single reference standard is less apparent for assessing the validity of observational estimates of forcefulness of exertion and is perhaps even less apparent for repetitiveness. Observational-based methods that have been reported for repetition and forcefulness of exertion make use of constructs that are often difficult to compare to a direct physical measurement. For example, the observed presence of stereotypical hand/

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wrist motions exceeding 50% of the work cycle has been used as an indicator of repetition in several studies (Silverstein *et al*. 1987, Chiang *et al*. 1993). However, this variable cannot be detected with any single measurement device. Ideally, observational-based methods for assessing risk factor exposure would be evaluated for accuracy against a single physical measure as a reference standard. However, this does not appear possible for several observational-based methods for evaluating the repetitive aspects of upper limb intensive work.

The purpose of the present study was to examine the relationships between observational estimates of upper limb activity and physical measures of work dynamics obtained by direct recording instrumentation. This was accomplished by quantifying the physical aspects of work activities related to upper limb kinematics and force exertion and comparing these to observational-based estimates made by analysts using methods consistent with those of common job analysis methods. A recent review by David (2005) summarised the exposure assessment methods that have been developed for systematic observation and documentation of work-related musculoskeletal disorder (WMSD) risk factors. Table 1 lists several studies that have used systematic observation to document the repetitiveness and forcefulness of exertion associated with upper limb intensive work. Some of the ways that repetition and upper limb activity/movement have been operationalised in observational job analysis methods do not lend themselves to direct comparison with any single physical measurement. In cases where no physically measurable reference standards could be defined, the inter-observer agreement of the methods was examined.

2. Method

2.1. *Simulation of jobs*

Five research associates acted as 'workers' performing six jobs in a laboratory setting. They were all right-handed males who were given a small amount of practice performing the jobs before the measurements and video recording were obtained. Workers 1, 2 and 3 performed jobs A, B, C and D. The heights of these workers were 177.0, 184.4 and 170.0 cm; their weights were 86.4, 80.3 and 69.5 kg respectively. Workers 4 and 5 performed jobs E and F. These workers were 182 cm and 188 cm in height and 83.7 kg and 86.0 kg in weight. All workers wore identical black sleeveless t-shirts while performing the jobs. In all jobs only the kinematics and forceful exertions of the dominant side (right) upper limb were recorded and analysts were instructed to observe and estimate only the kinematics and force exertions of the right arm.

Jobs A, B, C and D were simple tasks designed to require a variety of working postures of the upper limbs (see Table 2). Cycle times ranged from 8 s to 56 s and delineating transitions between individual work cycles was straightforward. Jobs E and F were simple tasks designed to require hand and shoulder force to use a powered drill with a hexagonal driver bit attachment to insert hexagonal lag screws into stud grade lumber (see Table 2). In job E, the holes were pre-drilled, longer lag screws were used and four lag screws were inserted per work piece. In job F, the holes were not pre-drilled, the lag screws were shorter and three screws were inserted per work piece. In the instruction materials analysts were provided with this background information about the jobs. Analysts were not informed that job E was intended to require

Table 1. Observational job analysis methods for assessing repetition and forcefulness of exertion of the upper limbs.

Parameter	Example reference(s)	Description
Cycle time	• Silverstein *et al*. (1987) • Chiang *et al*. (1993) • Armstrong *et al*. (1987)	typically represents a single unit of production
Count number of hand/wrist motions	• Drury (1987)	excursion of wrist in angular displacement exceeding a cut-point boundary
Frequency (number) of hand force exertions	• Stetson *et al*. (1991)	exertions/time
Hand force duty cycle	• Latko *et al*. (1997)	percentage of work cycle in which a hand force is exerted
Hand activity	• Latko *et al*. (1997) • ACGIH (2002)	hand activity level
Speed of work	• Moore and Garg (1995)	rating of speed of work similar to MTM framework
Estimates of velocity	• Spielholz *et al*. (2001)	average angular joint velocity
Magnitude of hand force	• Latko *et al*. (1999) • Moore and Garg (1995) • Occhipinti (1998)	visual analogue scale rating Borg CR-10 scale with collapsed categories Direct estimate of percentage of maximum exertion capability (or %MVC)

Table 2. Description of and risk factors assessed in the simulated jobs.

	Risk factors assessed	Description
Job A	Upper limb kinematics	Folding t-shirts
Job B	Upper limb kinematics	Assembly of small cardboard shipping boxes
Job C	Upper limb kinematics	Manual insertion of four screws with a standard screwdriver
Job D	Upper limb kinematics	Power-assisted insertion of five screws with a cordless drill
Job E	Upper limb force exertion	Power-assisted insertion of four lag screws in pre-drilled holes
Job F	Upper limb force exertion	Power-assisted insertion of three lag screws without pre-drilled holes

relatively lower force (by virtue of the pre-drilled holes in the wood) and job F relatively higher force (by virtue of not having pre-drilled holes in the wood). However, analysts could have readily inferred the relative force requirements between the two jobs based on the background information provided. This is similar to a true job analysis in which additional information about the task would typically be available to supplement the data obtained purely by observation.

2.2. *Apparatus*

Wrist and forearm kinematics were measured with a triaxial electrogoniometer system (Biometrics Ltd., Ladysmith, VA, USA). The system consisted of a single torsiometer to measure axial rotation of the forearm and a biaxial goniometer to measure flexion/extension and radial/ulnar deviation motions of the wrist. These devices have end blocks at the ends of a spring-sensing element. The end blocks are attached anatomically so that the sensing element spans the joint of interest with bend (goniometer) or axial twist (torsiometer) of the sensing element, creating a change in voltage output that can be calibrated to angular position. In an earlier study comparing estimates of working posture against electrogoniometric measures of angular wrist position using this system the radial/ulnar deviation measurements were not sufficiently reliable to be used as a measure of accuracy (Lowe 2004a). Therefore, the accuracy of repetitive aspects of wrist motions in radial/ulnar deviation were not reported.

Kinematics of the elbow and shoulder joints were reconstructed with a 3-D optical motion capture system (Peak Performance Technologies, Englewood, CO, USA) sampling at a rate of 60 Hz. Four cameras were used to reconstruct coordinates of seven reflective markers attached to the upper arm and thorax of the workers as described in section 2.5.2.

Hand and shoulder forces were derived from the normalised surface electromyogram (sEMG) recorded from the dominant arm finger flexor (flexor digitorum superficialis) and shoulder flexor (anterior deltoid). The sEMG was recorded from bipolar surface electrodes oriented in parallel with the muscle fibres as per published placement recommendations (Zipp 1982, Perotto 1994). The sEMG was detected with Ag/AgCl disc electrodes of 8 mm diameter and 21 mm inter-electrode distance. The differential amplification system had a Common mode rejection ratio (CMRR) of 87 dB at 60 Hz and a selectable gain. Raw sEMG was sampled at 900 Hz to a 12-bit A/D board (Keithley Metrabyte). sEMG data files were written in an ASCII file format and stored on a notebook computer.

2.3. *Analysts*

Ergonomists were recruited from academia and industry/consulting practice to participate in this study as job analysts. The criterion for inclusion was experience in performing analyses of jobs for the purpose of ergonomic assessment. The subjects recruited from academia were either full-time faculty with appointments in ergonomics-related programmes (e.g. Industrial Engineering, Occupational Medicine, Occupational Therapy) or advanced graduate students working under the supervision of such faculty, with experience in the area of upper limb musculoskeletal disorders. The ergonomists recruited from industry and consulting were practitioners who had experience with ergonomic evaluation methods and educational background and/or certification in ergonomics. Of the 29 analysts, nine held board certification in professional ergonomics. The experience in the field of ergonomics for these analysts averaged 9.1 years with a standard deviation of 6.6 years.

2.4. *Observational-based methods for force and repetition assessment*

2.4.1. *Upper limb force exertion magnitude*

Each analyst assessed the forcefulness of exertion for two jobs (jobs E and F) performed by one of two workers. Analysts were assigned randomly to these workers. Multiple work cycles were presented of each of the jobs on the video recording. Analysts reported an estimate for each variable for the 'typical' or 'average' work cycle, to reflect exposure to the forcefulness of exertion as averaged over the observed work cycles. These variables included three relevant aspects of the forcefulness of exertion:

(1) Peak of exertion was defined as the relative exertion associated with the task element(s) requiring the highest force exertion at the peak level of this exertion.
(2) Average of exertion was defined as the relative exertion corresponding to the average force over the duration in which a 'significant' force is exerted. A significant exertion was defined as relative activity exceeding 3% of maximum voluntary exertion. (The level of 3% was chosen to be in line with the criterion adopted by Latko 1997.)
(3) Average effort was defined as the effort level averaged over the entire work cycle, including periods of no force exertion.

These definitions, along with an example from a line graph of a force vs. time trace (normalised electromyogram (NEMG) on the y-axis and time on the x-axis) were provided to analysts in the detailed instruction materials they received.

Three methods for scaling the magnitude of each of these variables were evaluated. These methods were: (a) estimating a percentage of maximum voluntary exertion (%MVE) on a 0 to 100% scale for 1, 2 and 3 above; (b) estimating the level of exertion using the Borg CR-10 scale (Borg 1982) for 1, 2 and 3 above; (c) rating 1, 2 and 3 above by placing a mark along a continuous visual analogue scale (VAS) with verbal anchors at only the endpoints ('nothing at all' corresponding to a value of 0; 'greatest imaginable effort' corresponding to a value of 10).

2.4.2. *Estimates of force exertion duty cycle*

Force exertion duty cycle expresses the ratio of force exertion time to total cycle time. It was assessed by analysts using one of two methods. The first method involved estimating the duty cycle directly. Analysts were guided through this analysis based on their estimates of the number of arm force exertions per work cycle, the average duration of each force exertion and the average duration of the work cycle (cycle time). A significant arm force exertion was defined by an exertion of the shoulder (anterior deltoid) in transmitting force with the drill that exceeded 3% of the worker's MVE. The estimated duty cycle was calculated as the number of exertions multiplied by the average duration of exertion and divided by the average cycle time.

The second observational-based method for assessing the frequency and duration (temporal components) of force exertions was using the hand activity level (HAL) scale (see Figure 1), modified such that the analysts were instructed to focus on the temporal nature of the force exertions, rather than upper limb/hand motions. Analysts conducting this assessment were not instructed to use any pre-defined percentage of maximum exertion criterion for defining the presence of an exertion.

2.4.3. *Counts of wrist motions*

This measure was a numerical count of the number of times a joint displacement (in wrist flexion/extension and forearm pronation/supination) passed beyond a pre-defined neutral boundary and back within the neutral boundary. These counts were expressed as the number of excursions per work cycle. The boundaries defining the neutral posture were $\pm$ 30° for wrist flexion/extension and $\pm$ 40° for forearm supination/pronation. These boundaries are consistent with those adopted by Spielholz *et al.* (2001). Actual counts of wrist/forearm motions, based on the electrogoniometric recording, were averaged over the work cycles presented.

2.4.4. *Ratings of hand activity level*

Ratings of HAL were made using the VAS and method described by Latko *et al.* (1997). The scale, shown in

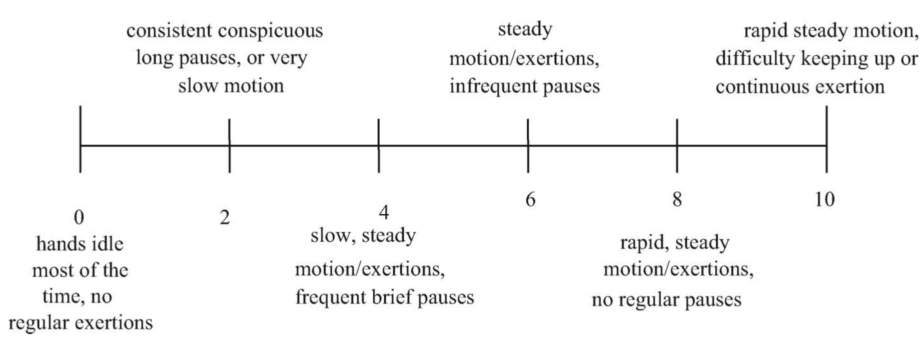

Figure 1. Hand activity level scale. (see Latko *et al.* 1997).

Figure 1, has verbal anchors describing the temporal characteristics of hand motions and hand force exertions and is numbered from 0 to 10 at the poles. The construct of HAL involves an integration of multiple dynamic aspects of upper limb use. The verbal anchors embody both the repetitive exertion of force by the hands and motions of the upper limbs. Thus, the selection of a single measurable aspect of the work dynamics against which the accuracy of a rating of hand activity level can be compared did not seem feasible. In the present study, the HAL scale was modified so that the activity of the upper limbs attributable to repetitive hand force exertions (consistent with the measurement of hand force) were rated separately from the activity attributable to upper limb motion (consistent with the measurement of upper limb kinematics). Since the HAL scale integrates both hand motions and frequency of hand force exertions, if the two variables are not differentiated it would not be possible to use a physical measurement to assess the accuracy of the analyst's estimate of the variable. This was the rationale for the modification to the HAL scale to include estimates of hand activity based on separate assessments of upper limb motion and frequency of hand force exertions. Analysts were specifically instructed to base their rating on either repeated hand force exertions or upper limb motions, depending upon whether they were assessing the force exertion or the motions of the upper limb.

2.4.5. *Ratings of speed of work*

Speed of work was rated by analysts using a five-category scale with verbal anchors of 'very slow', 'slow', 'fair', 'fast' and 'very fast' (Moore and Garg 1995). These anchors were originally established to match work paces relative to percentages ($<80\%$, 80–90%, 90–100%, 100–115%, $>115\%$, respectively) of standard times derived from the MTM-1 predetermined time system (Moore and Garg 1995). Rather than attempting to establish standard times via the MTM framework as a reference standard against which the analysts' ratings could be compared, inter-rater reliability among ratings of speed of work was examined.

2.4.6. *Estimates of velocity of the upper limb*

Estimates of joint angular velocities were obtained using a continuous VAS, in which the poles of the scale represented zero velocity (0) and maximum velocity (10). Analysts were instructed that maximum velocity referred to the 'maximum velocity possible for that joint'. No numeric value for maximum joint velocities was provided to analysts. Analysts estimated the peak and average movement velocity for each joint. All velocities were expressed in terms of their absolute value (positive), independent of the movement direction.

2.5. *Direct measurement*

2.5.1. *Hand and shoulder force*

The normalised sEMG was believed to be appropriate for quantifying the exertion of upper limb muscular force because of the static nature of the posture in which the forces were exerted in the powered screw-driving tasks. Raw EMG was digitally filtered with a sixth order Butterworth band pass filter (10–350 Hz pass band) and the root mean square (RMS) (50 ms) of the signal was calculated. The RMS EMG from the work cycles were normalised relative to maximum RMS EMG obtained from an average of three MVEs for both a static hand grip (flexor digitorum) and static forward elevation/flexion of the upper arm (anterior deltoid) against a fixed resistance. NEMG was calculated in the traditional manner: $NEMG = [RMS_{task} - RMS_{rest}]/[RMS_{max} - RMS_{rest}]$. Resting levels were obtained in a posture identical to that of the maximum levels, but without any generation of muscular force by the subject.

In the temporal analysis of force exertion, NEMG was used to identify the periods of force exertion based on a single threshold, defined by NEMG activity of the anterior deltoid exceeding 3% maximum voluntary contraction (MVC). This is illustrated in the Figure 2 example, which shows four clearly defined exertions corresponding to the insertion of four screws. Force

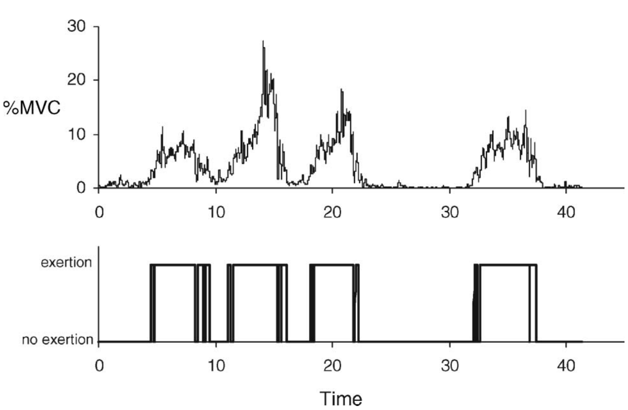

Figure 2. Example of electromyogram derivation of force duty cycle. The top panel shows the EMG relative activity, in units of percentage maximum voluntary exertion, the bottom panel shows the portions of the relative activity exceeding 3% maximum voluntary contraction (MVC). Using the 3% MVC threshold criterion there are four distinct exertions averaging 5.84 s each in a work cycle of 41.3 s duration. The EMG-derived duty cycle is thus 56.6%.

exertion duty cycle was calculated as the number of samples corresponding to exertion (>3% MVC) divided by the total number of samples in the work cycle. Periods of exertion defined by the shoulder exertion exceeding 3% of maximum were also used to define the time periods of hand force exertions for the purpose of calculating the average of the hand force exertions based on NEMG from the flexor digitorum. The rationale for this approach was that the act of simply holding and supporting the drill could result in an exertion level exceeding 3% MVC for the digit flexors. The anterior deltoid activity was indicative of periods during which arm force was exerted in driving a screw.

2.5.2. *Upper limb kinematics*

Kinematics of the wrist and forearm were measured electrogoniometrically. The electrogoniometer calibration procedure has been described previously (Lowe 2004a). Coefficients of determination between the calibrated electrogoniometer angle and the angle setting on the calibration fixture were 0.99 and 0.94 for wrist flexion/extension, and forearm supination/pronation.

Shoulder and elbow kinematics were calculated based on kinematic reconstruction of the position of seven reflective markers attached to the thorax and dominant arm of each worker. Three markers defined a local coordinate system on the humerus and three markers defined a local coordinate system on the thorax. A seventh marker was attached at the midpoint of the interstyloid line of the wrist. Global coordinates of each of the seven markers were calculated after low pass Butterworth filtering (5 Hz cut-off). Elbow posture was calculated as the inclusive angle between two vectors defined by three markers located at the mid-interstyloid line of the wrist, the lateral epicondyle of the humerus and over the middle deltoid. Shoulder posture was calculated by defining local coordinate systems for the humerus and thorax and establishing a sequence of Euler angle rotations to describe the orientation of the humerus with regard to the thorax. This procedure is described in detail in Lowe (2004b) and is similar to the method of Davis *et al.* (1998). Elbow angle is operationalised as the inclusive angle between the forearm and upper arm segments. Shoulder posture was operationalised with two angles describing the position of the upper arm with regard to the trunk – an angle of shoulder elevation and an angle describing the plane of shoulder elevation as viewed in the transverse plane (abduction/adduction).

Elbow flexion velocity and shoulder elevation velocity were calculated by kinematic reconstruction of angular joint position (posture) followed by smoothing and differentiation by finite differences. Kinematics of the upper limbs were summarised by expressing the velocity in absolute value form and then calculating the peak and average joint velocity by individual work cycle. These measures were averaged over the work cycles presented in the video recording.

2.6. ***Procedure***

Video recordings of the work cycles were obtained synchronously with measurement of the kinematics and the sEMG. The video recording was time synchronised with the instrumentation by a manually triggered LED pulse appearing visually in the video and appearing as a voltage pulse in an auxiliary analogue channel. Digital video recordings were made using a hand-held camcorder by ergonomists with experience in acquiring video of industrial jobs for the purpose of ergonomic evaluations. The video was edited so that the work cycles presented to the analysts corresponded to the portions of the sEMG recording that were used in calculating the measures of interest. Video footage of each job contained between five and 12 complete work cycles. The digital video was then transferred to VHS format to create multiple first-generation VHS format recordings that contained multiple work cycles of the jobs to be observed by analysts.

VHS-format cassettes were mailed to the job analysts along with all other study materials, which included data sheets and detailed instruction materials. Participants performed the analyses at their home institution, on their own time. They were instructed to observe the jobs on the video recording in the manner they were most comfortable. Analysts were compensated at a rate comparable to an hourly consulting fee for a professional ergonomist. Informed consent was obtained prior to the collection of data and all procedures had been approved by the Human Subjects Review Board at the authors' institution.

Multiple observational methods for assessing risk factors related to upper limb repetitiveness (repetition) and forcefulness of exertion (force) were evaluated. Analysts were assigned to a single method for the analysis of force and a single method for the analysis of repetition. They were assigned to observe one of the three workers perform jobs A, B, C and D for the assessment of upper limb repetition and one of two workers perform jobs E and F for the assessment of force exertion.

2.7. ***Data analysis***

Analysts returned their data recording sheets in hardcopy by mail to the investigators, at which time the data were entered into a formatted spreadsheet. VAS estimates of risk factors were normalised to the full-scale linear distance by physical measurement and were expressed as percentages of full scale. For risk factor variables with a direct-measurement reference standard data were expressed in terms of 'error' by subtracting the measured reference standard from the estimated value for the risk factor. This was done for the direct-measurements of variables for the specific worker the analyst observed.

In cases where no reference standard was attainable, or in cases where it was desirable to examine agreement among analysts' ratings using a particular scale, agreement was examined using intraclass correlation coefficients (ICCs). Linear regression coefficients of determination were calculated for continuous measures by regressing the estimated values against the direct-measurement values.

3. Results

3.1. Hand and shoulder force magnitude

Individual work cycles for jobs E and F consisted of either four (job E) or three (job F) identical elements requiring hand and shoulder force for insertion of a screw using the electric drill. Since the analysts were told how many screws were inserted in the work cycle, estimating the number of force exertions per work cycle was intended to be obvious, with the challenge expected to be in estimating the duration and magnitude of the force exertions. This was the case for all but two analysts.

Observational estimates of the magnitude of hand and shoulder force were generally higher than those derived from the NEMG. Some individual cases of force underestimation were observed, but the average differences between the estimated and measured force magnitudes were generally positive, indicating an overestimation bias. This bias was smaller for the peak hand and shoulder force than for the average hand and shoulder force (see Figure 3).

Figure 3 indicates that of the three scaling methods the VAS method was consistently associated with the largest overestimation bias. The Borg CR-10 scale and the %MVE scale appeared to be associated with less overestimation bias. No trends were evident among the three methods in terms of their precision, as reflected by the width of their standard deviation. Agreement among observers in their estimates of the magnitude of the force exertions were assessed by the ICC (see Table 3). Clear trends among the ICCs calculated for the three force scaling methods were not evident; however, direct estimation of percentage of maximum exertion, using the %MVE scale, was generally associated with a higher ICC.

3.2. Estimates of force exertion duty cycle

Two analysts exhibited difficulty with this analysis and provided estimates that were not only clear outliers within the dataset, but were infeasible by virtue of an estimated duty cycle for force exertion exceeding 100%. As an example, one of these ergonomists correctly identified four exertions per work cycle, but estimated the average cycle time as 22 s and the average duration of the hand force exertion as 8 s. This yields an estimated duty cycle of 145%, which is clearly infeasible. Whether this situation represented an error on the part of the analyst in documenting the estimate on the data sheet or a misunderstanding of the concept that was conveyed in the instructions is unknown. The fact that 14 of the 16 ergonomists who conducted this analysis provided not only feasible but also quite accurate estimates of force duty cycle suggests that the two cases of infeasible responses may have been attributable to errors on the part of the ergonomists in documenting their estimates rather than to problems in the conveyance of the concept. The two cases of infeasible responses were eliminated from the dataset in subsequent analyses.

When hand force exertion duty cycle was rated by analysts using the HAL scale, with specific instructions to derive their HAL rating based only on the repeated application of hand force, rather than hand motions, the resulting HAL score was closer to the measured duty cycle than when duty cycle was estimated directly (see Figure 4). Neither the HAL rating nor the estimated duty cycle exhibited any significant bias, as the differences between the estimated and measured values were not statistically different from zero. The ICCs were 0.070 for the duty cycle as estimated based on the duration of the exertion and cycle times and 0.103 for the HAL rating.

3.3. Counts of wrist motions

Table 4 lists the estimated and measured wrist/forearm motions by job and by worker. Inaccuracies in estimating counts of wrist motions were most obvious in the job with the greatest wrist/forearm dynamics, which involved the use of a screwdriver (job C). The correlation between the measured number of wrist motions and the count estimated by analysts was statistically significant for wrist flexion/extension motions ($F_{1,34} = 8.98$, $p = 0.005$, $r^2 = 0.209$) but was not significant for pronation/supination motions ($r^2 = 0.074$). When job C was excluded, the correlation between estimated and measured counts of wrist flexion/extension was $r^2 = 0.711$. The correlation was also improved for forearm supination/pronation ($r^2 = 0.147$) and was statistically significant ($F_{1,25} = 4.30$, $p = 0.049$).

The ranking among the jobs in terms of the severity of the number of wrist motions appears to be accurately reflected among the counts estimated by the analysts (Table 4). Job C was associated with the most

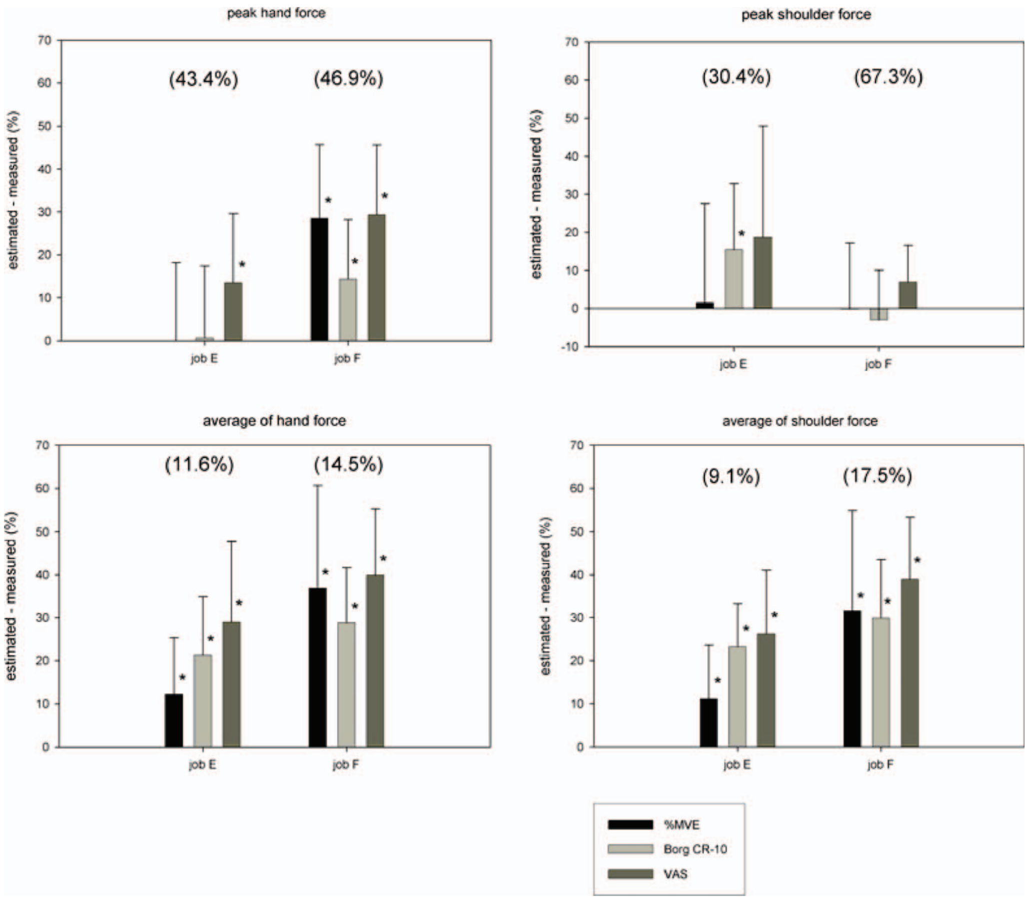

Figure 3. Mean analyst error for peak and average hand and shoulder force exertion level using the %maximum voluntary exertion (%MVE) scale, Borg CR-10 scale and visual analogue scale (VAS). The Borg CR-10 scale values were multiplied by 10 to be equivalent to the %MVE scale and the VAS. The bars indicate the mean differences between the estimated value and value measured from the normalised surface electromyogram (measured value shown in parentheses). Error bars show + 1 SD. *Indicates the conditions for which the mean error is significantly ($p < 0.05$) different from zero.

Table 3. Intraclass correlation coefficients for analyst estimates of hand force and shoulder force using the three methods of scaling force exertion.

	%MVE	Borg CR-10	VAS
Hand force			
Peak of exertion	0.776	0.304	0.366
Average of exertion	0.516	0.181	0.053
Average effort	0.508	0.052	−0.039
Shoulder force			
Peak of exertion	0.695	0.604	0.437
Average of exertion	0.531	0.376	0.539
Average effort	0.426	0.324	0.321

MVE = maximum voluntary exertion; VAS = visual analogue scale.

measured wrist/forearm motions followed by job D, job A and job B. This ordering matched that of the analysts' estimates exactly. Thus, while analysts may not have been able to provide exact counts of wrist and forearm motions for the jobs in an absolute sense, relative assessments among the jobs in terms of the number of wrist motions were completely accurate.

3.4. *Ratings of hand activity level*

Analyses were conducted to examine correlations between HAL numerical ratings and velocity of the joint motion rated as most influential on upper limb/hand activity. Analysts were asked to indicate which upper limb joint motion contributed the most to their overall perception of upper limb activity. Agreement among analysts in terms of the joint motion that was most influential on the upper limb activity was not strong (see Table 5), except for job C. In job C, 50% of analysts rated flexion/extension of the wrist as the most influential motion on upper limb activity and 40% rated forearm supination/pronation as most influential. No analysts rated the shoulder motions as most influential on upper limb activity. Thus, in job C,

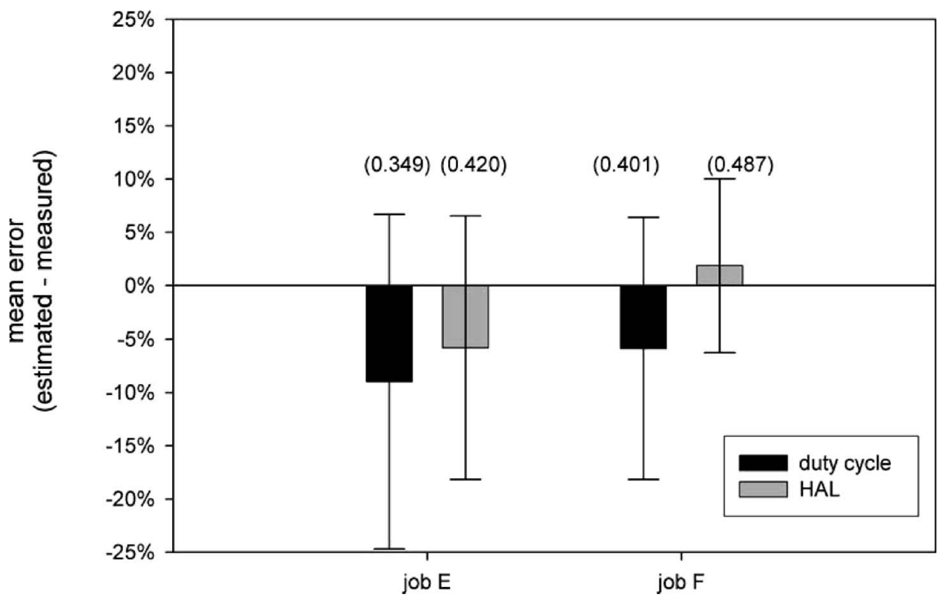

Figure 4. Mean error for estimates of hand force repetitiveness based on the direct estimate of hand force duty cycle and the hand activity level (HAL) scale. Measured duty cycle is based on the percentage of the work cycle in which the hand force exceeded 3% maximum voluntary exertion (MVE). The value shown in parentheses is the mean estimated level for that condition. Error bars represent $\pm$ 1 SD.

Table 4. Number of wrist (flexion/extension) and forearm (pronation/supination) motions calculated from the electrogoniometric measurements (measured) and estimated by analysts (estimated).

		Flexion/Extension		Pronation/Supination	
Job	Worker	Motions/cycle measured	Motions/cycle estimated*	Motions/cycle measured	Motions/cycle estimated*
A	1	14.0	5.3	8.9	3.7
	2	12.4	3.3	8.4	5.0
	3	12.5	4.7	4.1	5.0
B	1	5.4	2.7	1.9	1.3
	2	5.1	2.3	4.8	2.0
	3	4.8	1.7	0.9	1.3
C	1	58.4	29.3	63.4	39.3
	2	67.7	9.0	13.9	35.0
	3	80.1	27.3	1.9	70.0
D	1	22.7	6.3	12.6	10.3
	2	28.2	11.0	18.9	4.7
	3	21.3	10.0	6.5	9.7

*Mean value for n = 3 analysts per worker.

analysts agreed that it was the distal upper limb contributing most to the observed upper limb activity. The other jobs were more uniformly distributed among the joint motions rated as most influential on the upper limb activity rating. In these cases, analysts were not in agreement as to whether the distal or proximal upper limb was more influential in their assessment of upper limb activity.

Significant correlations between HAL ratings for the specific joint motion rated as most influential on upper limb activity and the measured joint velocity for this specific motion are shown in Figure 5. Significant correlations were found between wrist flexion/extension HAL ratings and average wrist flexion/extension velocity ($r^2 = 0.28$, n = 16, $p < 0.05$) and between forearm supination/pronation HAL ratings and peak ($r^2 = 0.50$, n = 8, $p < 0.05$) and average ($r^2 = 0.50$, n = 8, $p < 0.05$) supination/pronation velocity. Note that wrist flexion/extension was rated as the motion most influential on HAL in 16 cases and pronation/supination was rated as most influential in eight cases.

3.5. *Ratings of speed of work*

Analysts' estimates of the speed of work using the five-point scale are shown in Figure 6a (peak) and 6b (average). Average speed of work was rated as 0.66 to 1.11 points lower than the peak speed of work. The greatest agreement was in the rating of average speed of work for job C, in which 89% of the analysts assigned a rating of 3. The least agreement was in the rating of peak speed of work for job A, in which analysts assigned ratings of 2, 3, 4 and 5. Measures of agreement among analysts' ratings of speed of work yielded an ICC of 0.316 and 0.195 for average speed of work and peak speed of work, respectively.

Table 5. Percentage of analysts rating each joint motion as most influential in the assessment of overall upper limb activity using the hand activity level scale.

	Wrist flexion/ extension	Forearm supination/ pronation	Elbow flexion/ extension	Shoulder elevation	Shoulder abduction/ adduction
Job A	30%	20%	30%	0%	20%
Job B	50%	10%	20%	10%	10%
Job C	50%	40%	10%	0%	0%
Job D	33%	11%	22%	33%	0%

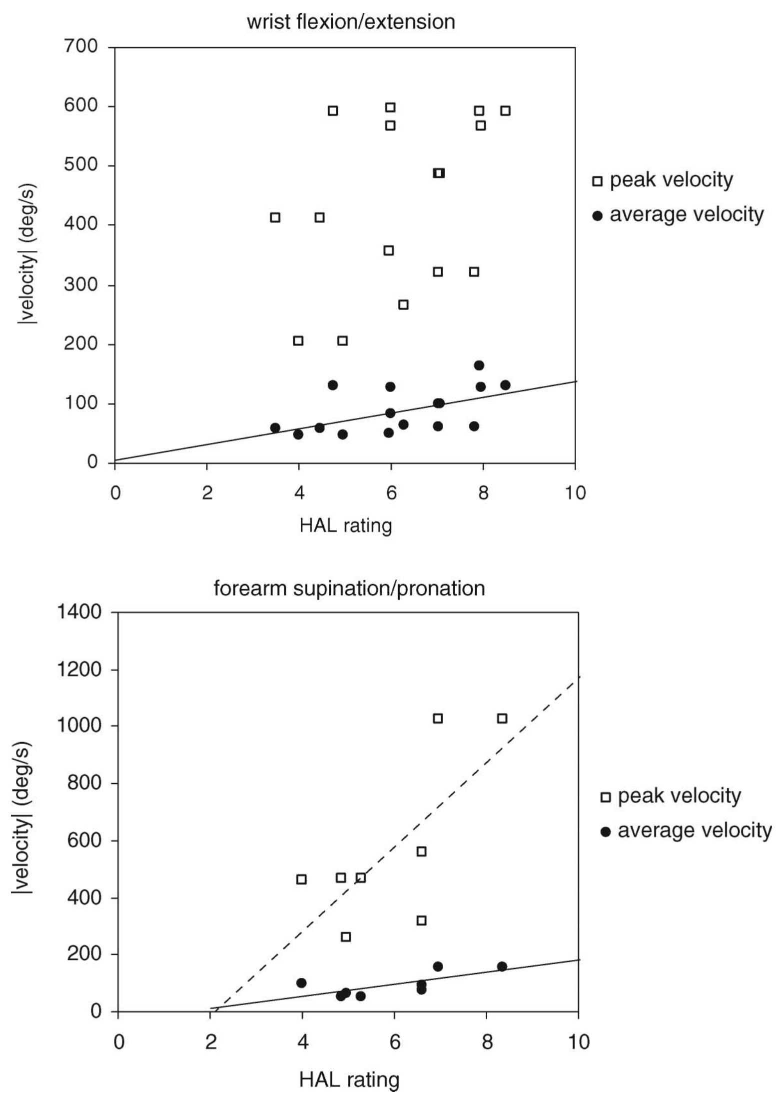

Figure 5. Ratings of hand activity level (HAL) as a function of movement velocity for the joint motion that analysts believed to be most influential in assessing overall upper limb activity. Statistically significant least squares regression lines are shown for average wrist flexion/extension velocity, peak forearm supination/pronation velocity and average forearm supination/pronation velocity.

3.6. *Estimates of velocity of the upper limb*

Estimated joint velocities (peak and average) using the continuous VAS were regressed against the measured velocities for these joint motions as recorded by direct measurement. Correlation coefficients for these models are listed in Table 6. Significant correlations ($p < 0.05$) were observed for peak wrist flexion, peak wrist extension, average wrist flexion/extension, peak

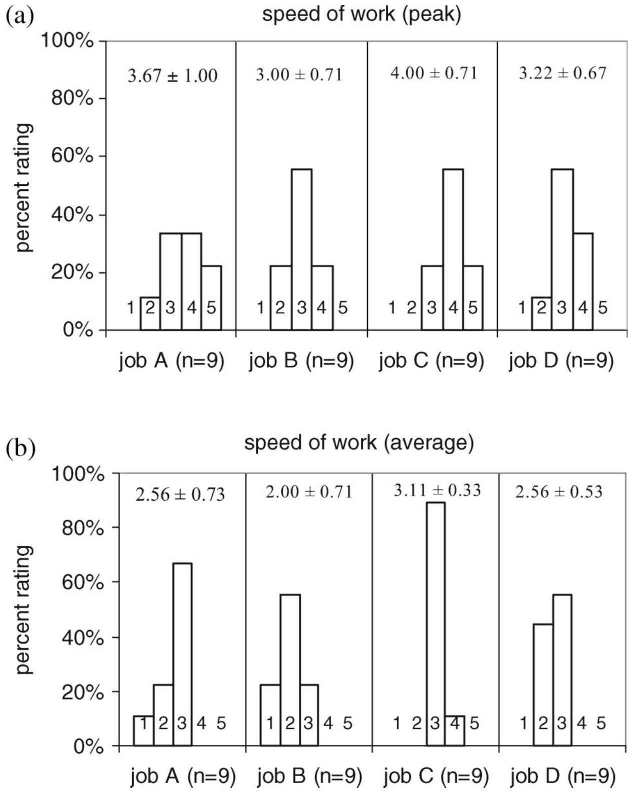

Figure 6. Distribution of ratings of the speed of work from the strain index. The ratings represent: 1 = very slow; 2 = slow; 3 = fair; 4 = fast; 5 = very fast.

Table 6. Results of regression models for estimated vs. measured velocity.

	r	*p*
Peak flexion	**0.528**	**0.0009**
Peak extension	**0.417**	**0.0114**
Average flexion/extension	**0.448**	**0.0061**
Peak pronation	0.200	0.2422
Peak supination	0.288	0.0890
Average pronation/supination	0.168	0.3263
Peak elbow flexion	0.209	0.2212
Peak elbow extension	**0.355**	**0.0337**
Average elbow flexion/extension	**0.358**	**0.0319**
Peak shoulder elevation	**0.329**	**0.0497**
Average shoulder elevation	0.225	0.1872
Peak shoulder abduction	0.252	0.1377
Average shoulder abduction	**0.394**	**0.0193**

Note: Results in boldface denote statistical significance ($p < 0.05$).

elbow extension, average elbow flexion/extension, peak shoulder elevation and average shoulder abduction (plane of shoulder elevation).

4. Discussion

The validity of job analysis methods for assessing physical risk factors for WMSDs should be based on how well they predict incidence of WMSDs, their external validity and how accurately they reflect true levels of physical risk factors, their internal validity (Kilbom 1994). The present study addressed the issue of internal validity of observational-based assessments of repetition and forcefulness of exertion using methods representative of those that have been published in the literature. Methods such as the HAL scale, which integrates multiple aspects of the work dynamics, can be broken down into the component variables (i.e. upper limb motions and repeated force exertions), so that these can be assessed individually for comparison with the relevant instrumentation-based measurement. The differentiation of upper limb motions from upper limb exertions may depart from the concept of the HAL method. However, without isolating the component variables and having the analyst rate these independently, it would not be possible to evaluate the accuracy of any aspect of the estimate. In the present study analysts' ratings of HAL, when instructed to assess hand force exertions, compared favourably with the EMG-derived duty cycle for force exertion. Analysts' ratings of hand activity when instructed to assess hand motions exhibited a weaker association with movement velocity of the upper limb.

The count of wrist motions obtained from electrogoniometric recordings based on a single pre-defined angular displacement cut-point was sometimes worker-dependent, as in the case of job C. Job C also represented a case in which many repetitive forearm rotations were evident in the work cycle, but where the visual determination of whether these rotations exceeded the cut-point boundary in pronation/supination (40°) was difficult. The forearm rotations of worker 1 in job C frequently exceeded the cut-point (63 forearm pronation/supination motions per work cycle), but for workers 2 and 3 they did not (13.9 and 1.9 motions per work cycle). These workers exhibited hand/wrist motions – but not motions that exceeded the cut-point. Analysts' estimates of 39, 35 and 70 forearm rotations per work cycle for workers 1, 2 and 3 indicated that they perceived that the repetitive forearm rotation motions did exceed the cut-point boundary. Wrist flexion/extension motions exhibited a somewhat reversed effect, in which the analysts reported fewer repetitive flexion/extension motions exceeding the cut-point boundary than were measured with the electrogoniometer. An analyst may be able to detect directional changes in the displacement of the joint, but a misperception of the angular cut-point boundary can result in a large error in the count of motions referenced to this cut-point.

When normalised electromyographic activity served as a reference standard of force exertion magnitude, the study results indicated that force exertions of the hand and shoulder were generally lower than analysts' observational-based estimates indicated. The explanation for what appears to be a tendency toward overestimation of force exertion is unclear. In a few cases, analysts clearly overestimated force exertion based on physiological limitations and recovery needs from repeated muscular exertion. One analyst rated peak of exertion as high as 90% of maximum and in one instance an analyst rated average of exertion as 84% of maximum, with an estimated duty cycle of 47.6% (20 s of exertion time in a 42 s work cycle). This level of exertion sustained for this duration is unlikely to be physiologically possible and is clearly an overestimate for this job.

In spite of these few atypical cases, the overall accuracy of analysts' estimates of peak hand and shoulder force were reasonable when compared to the NEMG. By comparison, analysts were less accurate in estimating average hand and shoulder force. Estimates of the peak force exertion were expected to be more accurate than those of the average, since estimating the average level involves greater cognitive integration of the variable that is being assessed. Peak force exertion is also more prone to a ceiling effect where the degree of possible overestimation is lower.

Observers in Marshall and Armstrong (2004) estimated forces from video clips of subjects simulating common forceful hand activities on a work simulator device. While the reference standard for force exertion in their study was the force output from sensors in the work simulator, which may be a more desirable reference than the normalised sEMG used in the present study, the work simulator device may reflect a work task for which force exertion is more difficult to estimate than the simulated jobs in the present study. The use of a powered screwdriver represents an activity that analysts have some personal frame of reference by which to assess the typical force requirements. In addition, analysts were provided with some background information (i.e. whether or not the holes were pre-drilled and the depth of the screw insertion) that may have given them a frame of reference to estimate force exertion levels with the powered screwdriver. This would explain what appears to be slightly larger variability among the estimates of force exertion reported by Marshall and Armstrong (2004) relative to that of the present study, particularly in the medium force range, which was most applicable to the exertion levels in the present study. Marshall and Armstrong (2004) also reported a central tendency bias, in which analysts overestimated low force and underestimated high force. No such tendency was observed in the present study, in which the force levels were generally overestimated.

Results of the present study indicate that differences in accuracy among the methods for scaling the magnitude of force exertion were small. The direct estimate of %MVE resulted in slightly more accurate estimates; however, the choice of scaling method did not appear to be an important source of error. Several job analysis methods have been developed based on the Borg CR-10 scale ratings of force exertion. The Borg CR-10 scale was developed as a psychophysical scale to be used by the individual performing the exertion and experiencing the physiological effects of the exertion. Little is known about the validity of the CR-10 scale when it is used by an observer to estimate someone else's physical exertion. The results of this study suggest that the Borg CR-10 scale was equal or slightly greater in accuracy than the VAS approach, but was no more accurate than a direct estimate of the worker's relative exertion level (%MVE).

Anecdotally, analysts indicated that the estimation of force magnitude by video observation alone was difficult. The fact that the analysts did not have the opportunity to observe these jobs first hand may have added to this difficulty. This may also reflect a larger error than would be expected in other realistic job analysis situations. In a realistic job analysis situation the analyst would typically observe the job in the field and would thus have access to other information regarding the work process on which estimates of the manual force requirements of the job could be based. In many cases, the ergonomist would perform the exertion, so as to personally experience the exertion required, or assess the forcefulness of exertion using an indirect measurement technique such as psychophysical force estimation (Drury 1987, Hoozemans *et al.* 2001), measurements of the weights of parts handled (Pope *et al.* 1998) or push/pull forces required (Hoozemans *et al.* 2001) or simple biomechanical models (Stetson *et al.* 1991).

The hand force duty cycle appeared to be more reliably estimated by analysts than the magnitude of the forces. Conspicuous events are frequently observable as visual cues to assist analysts in estimating the occurrence of task elements requiring an exertion of force based on the start and end of the exertion period. For example, in the present study, observing the physical contact between the electric drill bit and the screw in the wood served as a visual cue that the drilling force was about to begin or end. Visual cues to assist in estimating the magnitude of the worker's force exertion are less conspicuous and are likely to be less reliable. Cues related to fluidity of the exertion, muscle bulging and qualitative facial expression (Moore and Garg 1995, Marshall and Armstrong 2004), have been suggested, but the reliability of such cues has not been well demonstrated.

Assessment of the upper limb kinematics involving repetitive wrist and forearm motions suggested that while analysts' estimates of these motions suffered from some inaccuracies in an absolute sense the estimates accurately reflected the relative differences between the jobs in terms of the severity of the repetitive motions. Thus, it appears that analysts may be accurate in prioritising jobs in terms of the severity of wrist/forearm repetitive motions in a relative sense, but that estimating the level of this exposure in an absolute sense (through an accurate count of repetitive motions) would be less reliable. The study data suggest that the more complex the activity, the greater the error in estimating a count of repetitive motions.

Fransson-Hall *et al.* (1995) compared five observers' estimates of repetitive movements of the hand to 'reference' values, which were based on two scientists' observational assessment of the variables. High agreement between the observers' estimates and the reference value was reported in the job that exhibited no repetitive hand movements (furniture moving). The other jobs exhibited lower agreement. There are few other studies in which a direct comparison between electrogoniometrically measured wrist motions were compared to estimates of wrist motions based on a predefined cut-point. Spielholz *et al.* (2001) reported Pearson product-moment correlations (r) between measured and estimated number of wrist motions of 0.32, 0.27 and 0.53 (flexion/extension, radial/ulnar deviation, and pronation/supination respectively) for jobs that exhibited between nine and 20 repetitions per min. Correlations between the measured and estimated counts of wrist motions observed in the present study ($r = 0.457$ for flexion/extension and $r = 0.272$ for pronation/supination) were only slightly lower than those reported by Spielholz *et al.* (2001), but were reversed in the fact that a higher correlation was observed for flexion/extension than pronation/supination. This may be explained by the more dynamic nature of the jobs in the present study. In the present study, job C was associated with 73 wrist flexion/extension repetitions per min and the least dynamic job was associated with 16 pronation/supination motions per min. When the job with the most dynamic upper limb motions (job C) was removed, the correlations between measured and estimated counts of wrist flexion/extension and forearm pronation/supination motions were higher ($r = 0.843$ for flexion/extension and $r = 0.383$ for pronation/supination) than those reported by Spielholz *et al.* (2001).

Assessing the validity of ratings of upper limb motion using the HAL scale is limited by the fact that work is made up of motions of multiple upper limb joint segments, whose motions must all be taken into account when providing a single rating for upper limb motion. In the present study, the strategy was to have analysts select the upper limb joint motion that contributed the greatest to their perception of upper limb activity. Analysts then rated this joint motion on the VAS. Latko (1997) compared HAL ratings with the measured angular velocity of the wrist in the more dynamic plane of motion – either flexion/extension or radial/ulnar deviation. Latko's reported correlation of 0.57 is similar to that of 0.50 obtained in the present study when regressing pronation/supination angular velocity against the HAL rating, when analysts rated pronation/supination as the most influential joint motion on the HAL.

Spielholz *et al.* (2001) reported a large overestimation of wrist motion velocity when analysts used the VAS method to estimate joint velocity directly. In order to make the measured wrist velocity levels comparable to the VAS estimates, velocity was normalised to the '... highest values while performing the task studied'. This approach assumes that the highest velocity in the tasks studied would be equivalent to the scale anchor of 10 on the VAS. The decision was made in the present study to make no assumptions about the angular joint velocity anchored to a rating of 10 on the VAS, since maximum functional movement velocities for the purpose of evaluating work activities have not been established. Thus, the analyses did not address error between the measured and estimated velocity, but addressed the correlation between measured velocity and the velocity estimated by analysts using the VAS. The correlations between estimated and measured velocity were slightly higher than those reported by Spielholz *et al.* (2001), particularly for wrist flexion/extension.

The question of how much inaccuracy in the evaluation of physical risk factors for WMSDs is acceptable relates to the precision requirements of the analysis. For example, the continuous HAL scale has been presented with three categorical levels (low, medium, high) with regard to a threshold limit value (Latko *et al.* 1999). Similarly, Rucker and Moore (2002) partitioned the continuous strain index scale into 'hazardous' or 'safe' levels based on a strain index score threshold of 5.0. When the scales are partitioned in this manner, inaccuracies in estimating the exposure variables are less critical so long as they are not errors occurring near any of the boundaries between exposure categories. Conversely, some intervention studies have compared work practices by treating job analysis outcome scores as continuous measures without creating categorical levels for the definition of risk (e.g. Massaccesi *et al.* 2003, Choobineh *et al.* 2004). In one case, the difference in scores between workstation configurations in a rapid upper limb assessment (RULA) assessment pre- and post-ergonomic intervention was found to be only 0.22

(grand scores of 6.67 vs. 6.89). While this difference was reported to be statistically significant the degree of precision of an observational-based method such as RULA could be limited by the accuracy of the physical exposure estimates, which are inputs to job analysis method.

The observational-based methods for estimation of repetition and forceful exertions in the present study were examined as 'pencil and paper'-based methods in which the analysts had access to a video recording showing a single camera view of the worker and basic analogue video playback functions. The basic video playback functions included capabilities for pause, slow motion playback and frame advance/reverse of analogue video tape. All documentation and recording of the exposure variables of interest were made by the analyst in their own format, which were transferred and submitted on a formatted hand-written data sheet. Analysts in the present study did not have the benefit of a computer-assisted playback or job/task analysis system. Some observational-based ergonomic job/task analysis methods have been computerised so that the documentation of exposure event transitions can be made through a computer interface with resulting exposure frequencies and durations calculated by the software (Keyserling 1986, Yen and Radwin 2002). The systems assist the analyst mainly by performing the frequency/duration calculations in the software based on the analyst's delineations of exposure event category transitions. Further study of the benefits of these systems is needed, particularly in the assessment of the forceful exertion frequency and repetitive aspects of upper limb intensive work.

A limitation of the present study was that the investigators were not able to directly monitor analysts as they conducted these observational-based job analyses. Therefore, limited knowledge was obtained regarding specific observational strategies adopted by analysts in their use of video playback controls and how, qualitatively or quantitatively, the video segments were viewed prior to estimation of individual risk factor levels. Analysts received specific written instructional materials that outlined the sequence for analysing jobs and risk factors within jobs. This was done in an attempt to standardise the analysis approach to the degree feasible without the investigators being present during the analysis. The decision to send study materials to analysts enabled a larger sample size than would have been attainable had the analysts been required to travel to the investigators' institution, or vice versa. However, additional qualitative insight might be gained by directly observing specific video observation strategies employed by analysts.

5. Conclusion

The present study findings suggest that job analysis methods relying on systematic video observation to assess force exertion and upper limb motions should be applied with consideration given to the capabilities and limitations of ergonomists in estimating these risk factors. Results of the present study indicate the following:

- Ergonomists performing job analyses were able to estimate the temporal aspects, such as duration and frequency, of forceful exertions more accurately than the magnitude of the exertions.
- Analysts tended to overestimate the peak of the forceful exertions, but to a lesser degree than the overestimation of average level of exertion over the duration of the force output.
- Data from the present study and others (Latko 1997, Spielholz *et al*. 2001) suggest that estimates of the velocity of the upper limbs in hand-intensive tasks are not reliable, as evidenced by a weak correlation with measured velocity.
- Job analysts' counts of repetitive motions of the wrist and forearm, defined as estimates of individual motions of the joint beyond a defined neutral category boundary and back, appeared to be reliable in assessing the relative severity of the repetitive motions among several jobs. However, analysts' counts of these motions were not accurate in absolute terms, particularly in jobs that were more complex in terms of upper limb movements.

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