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Mechanical Exposure Variability in Industrial Assembly Work

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List of papers

This licentiate thesis is based on the following studies, which are referred to in the text by their Roman numerals:

I. Mathiassen SE, **Möller T**, Forsman M. Variability in mechanical exposure within and between individuals performing a strictly controlled industrial work task. Submitted

II. **Möller T**, Mathiassen SE, Franzon H, Kihlberg S. The influence of job rotation on mechanical exposure variability in cyclic assembly work. Submitted

Abbreviations

EMG	Electromyography, a method for measuring the electrical activity in muscles
RMS	Root Mean Square
MVE	Maximal Voluntary Electrical activity
RVE	Reference Voluntary Electrical activity
EVA	Exposure Variation Analysis
ANOVA	Analysis of Variance
CV	Coefficient of Variation
CI	Confidence Interval

Contents

1. Introduction

1.1 The scope of this thesis

Many industrial tasks tend to decrease in their span of available mechanical exposure (physical load) and become more similar i.e. more repetitive and monotonous. Hence, an increased variation within jobs, both physical and mental variation, is a common suggestion for ergonomic intervention (Kroemer et al., 1997). By applying different strategies for work enlargement i.e. job rotation and enriching the content of work tasks, it may be possible to achieve more variation, but few intervention studies have documented results in terms of variation. Analysis of mechanical exposure variability data may be one way to facilitate the evaluation of variability in work tasks and may also function as a measure of motor flexibility and work technique. Another important purpose for analysing exposure variability data is to improve and develop more effective measurement strategies in the planning of ergonomic intervention studies.

This licentiate thesis is part of a multi-disciplinary Research & Development programme called COPE (Co-operation for Optimization of industrial production systems regarding Productivity and Ergonomics (Winkel et al., 1999)) funded by the National Institute for Working Life. The main purpose of the programme was to find more effective and sustainable ways to intervene towards improved ergonomics by integrating ergonomic considerations in the continuous development of production systems. The research was performed in the form of case studies at industries planning for interventions in the production system.

1.2 Work-related musculoskeletal disorders

Work-related disorders cost Swedish society nearly five per cent of the gross national product. Musculoskeletal disorders are the most common work-related disorders and account for approximately one third of the cost, as these caused every third report of absenteeism from work from 1998 to 99 (National Board of Occupational Safety and Health & Swedish Statistics, 1999a). Data from the same source shows that the average sick leave due to work-related musculoskeletal disorders in 1998, was 124 days for illnesses and 44 days for accidents, while the average sick leave was 105 days for work-related illnesses and 30 days due to accidents. The number of reported musculoskeletal disorders was 12,000 in 1999, which was a 20 % increase compared to the previous year (National Board of Occupational Safety and Health & Swedish Statistics, 1999a). The proportion of reported musculoskeletal disorders in the shoulders and arms in the working population, increased for women from 35 % to 38 % and for men from 21 % to 24 % between 1997 and 1999 (National Board of Occupational Safety and Health & Swedish Statistics, 1999b)

1.3 Risk factors for work-related musculoskeletal disorders

Epidemiological studies show that the development of work-related musculoskeletal disorders may be attributed to an array of risk factors, both of physical and psychosocial origin (Bernard, 1997; Buckle et al., 1999). There are a number of studies indicating that repetitive work, static loading and awkward postures have an effect on the development of musculoskeletal disorders. Psychosocial risk factors that have shown to be related to musculoskeletal disorders include high work demands, experiences of job stress, and monotony (Bernard, 1997). Hence, the mechanisms leading to disorders are probably products of interactions of several risk factors and the whole picture remains to be solved. Several of the mentioned risk factors have a common denominator: lack of variation. Thus, lack of variation has been specifically pointed out as a risk factor, comprising mechanical as well as psychological elements (Hagberg et al., 1995; Kilbom et al., 1987). Variation in the load pattern of individual muscles has been shown to be important for muscle endurance (Mathiassen et al., 1998; van Dieën et al., 1993). However, few methods have been suggested for quantifying 'variation' in occupational work.

Statistics of the Swedish work force show that 44 % of the women and 34 % of the men experience that they repeat the same work task many times per hour during at least half of their time at work. A third of the women and a fourth of the men experienced stressful and repetitive work movements (National Board of Occupational Safety and Health & Swedish Statistics, 1999b). Furthermore, the work is considered fixed and constrained by 22 % of the women and 16 % of the men. About 50 % of the workforce experience that they are able to decide their own work pace for less than half of the time and that they seldom or never can decide when to perform different work tasks (National Board of Occupational Safety and Health & Swedish Statistics, 1999b).

1.4 Mechanical exposure

Mechanical exposure, often called physical workload, refers to the forces, which are generated by the operator to meet the work demands caused by the production system (external exposure, figure 1). By definition external exposure is quantified independently of the worker and preferably in the three dimensions: *level*, *frequency* and *duration* (van der Beek et al., 1998; Westgaard et al., 1997; Winkel et al., 1994). Examples of external exposures are work organisation schemes and workplace design. The results of the work demands are biomechanical forces acting on and in the musculoskeletal system of the worker, which is called internal exposure, and these may be estimated by measurements on the individual worker (Westgaard & Winkel, 1997). Hagberg and co-authors called this concept 'dose' in a similar model, however dose is 'internal exposure' multiplied by duration (Hagberg et al., 1995). The internal exposure, in turn, generates acute responses, which are defined as short-lasting, reversible physiological or psychological changes experienced by the individual worker.

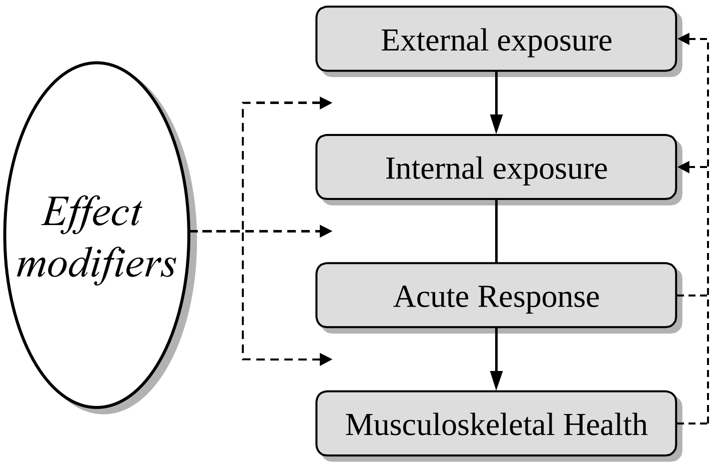

Figure 1. A conceptual model of the relation between external exposure and musculoskeletal health revised from Winkel & Mathiassen (1994) and Westgaard & Winkel (1997).

Over time, these responses create more long-lasting effects on the musculoskeletal system that may be of either positive or negative character for the musculoskeletal health. Training effects that improve the musculoskeletal health would be regarded positive, while disorders or injuries are examples of negative health outcomes. The acute response and the musculoskeletal health also have a feedback effect on the internal and external exposure, shown by the dotted arrows on the right side of figure 1. Effect modifiers are a collective term for factors of environmental- or individual-related character that may influence the relation between the different elements described above (grey boxes). Examples of environmental factors are temperature, psychosocial climate; and examples of individual factors are work technique, experience, gender, age and anthropometrical measures.

Variability may occur at all stages of this model (figure 1). Contributions to the variability of the external exposure fronting the individual come from the same external factors as mentioned above (e.g. workplace design, work organisation and task allocation). Factors affecting the variability of internal exposure are the same as the effect modifiers in this model. Internal exposures have been shown to vary considerably, both within and between individuals faced the to the same work task - external exposure (Hammarskjöld et al., 1989; Veiersted et al., 1993). However, few studies have systematically explored exposure variability in different types of tasks and populations.

1.5 Repetitive work

As stated before, repetitive manual work is a commonly accepted risk factor for musculoskeletal disorders, particularly for the upper extremities (Bernard, 1997; Hagberg et al., 1995). The term repetitiveness has been used to quantify the time variation in work, but the definitions diverge (Hagberg et al., 1995). Two essentially different expressions of ‘repetitiveness’ in mechanical exposure have been proposed in the literature: the *similarity* in repeated actions (Kilbom, 1994) and the *frequency* of movements or muscle activity (Ohlsson et al., 1994; Radwin et al., 1993).

The first concept requires measures describing similarity, also called sameness and invariability, between consecutive periods of work e.g. cyclic performances of a work task or performance in different work hours (figure 2) (Mathiassen et al., 1995a). Similarity may be assessed with respect to all three basic dimensions of exposure, i.e. the level, the frequency and the duration (van der Beek & Frings-Dresen, 1998; Winkel & Mathiassen, 1994), as well as for exposure templates as used in studies of motor control (Kjellberg et al., 1998; Madeleine et al., 1999; Winter et al., 1987). However, very few ergonomic studies have used quantitative measures of similarity and compared different tasks or jobs in this way.

The second approach in order to quantify repetitiveness is to analyse the frequency dimension in exposure recordings (Hagberg et al., 1995; Mathiassen & Winkel, 1995a; Radwin & Lin, 1993). Frequency in this context is defined as the number of shifts per time unit between force amplitudes in a target tissue (figure 2). Examples of expressions of frequency related to musculoskeletal load are: gap frequencies in EMG (Veiersted et al., 1990), frequency of shifts between angular posture categories (Kilbom & Persson, 1987), frequencies of movements (Balogh et al., 1999; Ohlsson et al., 1994; Radwin & Lin, 1993) and arrays of Exposure Variation Analysis (EVA), which indirectly reports frequency as relative time spent without interruptions in specified exposure categories (Mathiassen et al., 1991).

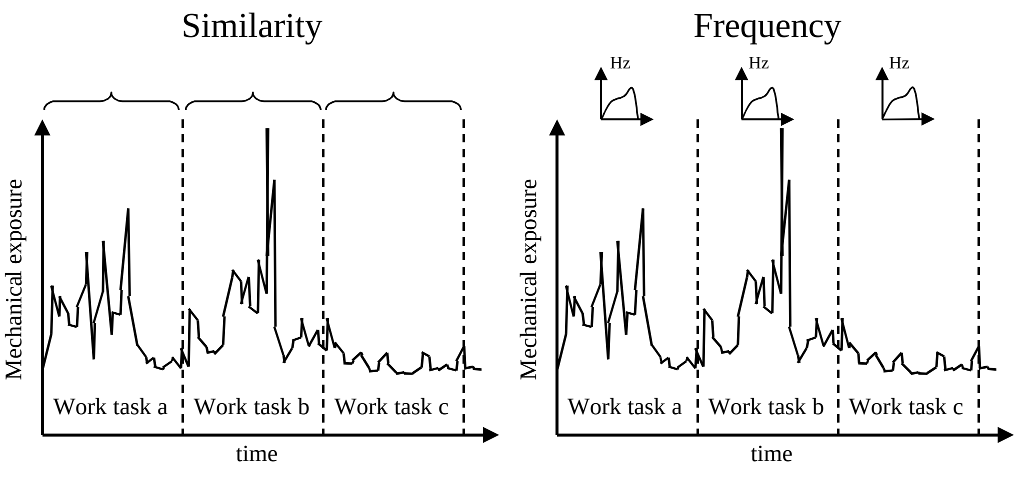

Figure 2. An illustration of exposure *frequency* and *similarity*. Similarity measures the equality between work tasks and frequency measures the number of shifts between amplitudes of mechanical exposure in the studied tissue. The figure is based on Mathiassen and Winkel 1995 (Mathiassen & Winkel, 1995a).

Assembly work is generally considered as highly repetitive, unvarying work, in the sense that similar work operations are repeated for extended periods of time, which may also be the main cause of the high risks of musculoskeletal disorders in the upper extremities in this occupation (Kilbom & Persson, 1987), i.e. assembly work dominated by operating powered hand-held tools (Nathan et al., 1988; Rempel et al., 1992) and manual assembly of electronic components

(Kilbom & Persson, 1987). In Sweden, general assembly work engages 48,000 workers and electronic assembly, including electronic repairmen, involves 28,000 workers. Approximately 20 % in both groups are women. Assembly work belonged to the occupations with most reported musculoskeletal disorders among women in 1998 (National Board of Occupational Safety and Health & Swedish Statistics, 1999b). 23 % of the vehicle assemblers and 36 % of the electronic assemblers reported experiences of pain in the upper back and neck within the last week. 34% of the vehicle assemblers and 27 % of the electronic assemblers experienced pain in the shoulders or arms within the last week (National Board of Occupational Safety and Health & Swedish Statistics, 1999b).

1.6 Ergonomic interventions

In a review, Westgaard and Winkel concluded that the main purpose of most ergonomic interventions has been to improve the workers' health by reducing the mechanical exposure level rather than its frequency or duration (Westgaard & Winkel, 1997). To reduce the level, attempts were made to improve the workplace or the tool design, sometimes in combination with health education, physiotherapy or different types of exercise. Even though many ergonomic interventions take place, the number of reported work-related musculoskeletal disorders is still increasing in Swedish society, as described above.

Intervening with the purpose of increasing physical and mental variation in the job has become a common suggestion for decreasing the risk of upper extremity disorders. Examples of ergonomic interventions that may lead to increased variation in exposure are: increased opportunities for (1) using different work techniques, e.g. alternating between working postures, (2) deciding one's own work pace, (3) enlarging the work tasks or (4) rotating between work tasks (Canadian Centre For Occupational Health and Safety, 1989; Kroemer & Grandjean, 1997; National Board of Occupational Safety and Health, 1998). Job enlargement may also have an enhancing effect on product quality as well as productivity (Axelsson, 2000; Loven, 1994). Additional reasons for job enlargement are increased motivation among the work force by offering an array of tasks (Campion et al., 1991; Cocke et al., 1993; Pires et al., 1997) and reduced average risk of develop disorders by distributing hazardous exposures across several workers (Ekberg et al., 1994). However, there are studies that show that job enlargement may convey both reduction and increase in risk (Frazer et al., 1999; van Dieen et al., 1994). A multi-skilled work force may also be an important asset when there is a need for filling in for absent workers and during rapid changes in production. However, if job enlargement implies performing more of the same in example rotation between work tasks with similar exposures, the advantage may be limited from a psychological as well as a physiological (mechanical) point of view (Jonsson, 1988; Kroemer & Grandjean, 1997). Thus, there is a need for methods, which can quantify similarity between work tasks, and the effect of job enlargement on similarity.

1.7 Ergonomic applications of mechanical exposure variability

Exposure variability as a measure

The review given above suggests that it would be interesting to explore the use of simple exposure variability measures as descriptors of ergonomically important characteristics of tasks and jobs, as well as of individual motor performance strategies in an ergonomic context. A particular interest appears in repetitive work, where similar operations are repeated again and again (Kilbom, 1994).

Variability within individuals provides information on the similarity in mechanical exposure between periods of work for a specific individual, which may serve as information about the flexibility in work technique of that specific individual. The variance within individuals may also give indications of the dynamic character of a work task, with a high value representing dynamic or variable work task. Thus, the variance within individuals depends partly on the degrees of freedom offered by the work task under existing conditions, and partly on the utilisation/adaptation of these degrees of freedom by the individual. A straightforward interpretation of the size of a variance is therefore not possible. For instance, a new employee may apply a more varying work technique, and thereby get a larger variance, than a more experienced or skilled operator.

Variability between individuals may reflect the allowance offered by the work task for individual performance strategies for a group of workers. The task variance between individuals, stripped from the contribution of variance within individuals, may provide information about the range of performance strategies allowed by the task. Again, a large variability is not an unambiguously positive sign. For instance, a non-adjustable workstation will result in large between-subject exposure variability, due to different anthropometry among the work force.

Strategies for exposure assessments

Accurate and precise methods for exposure assessments are important prerequisites for establishing useful exposure-outcome relations, as well as for correct interpretation of the results of intervention studies (van der Beek & Frings-Dresen, 1998; Westgaard & Winkel, 1997; Winkel & Mathiassen, 1994). Methods based on direct technical recordings of mechanical exposure have been recommended, since they offer data at a higher resolution and with better accuracy than observations or self-reports. Exposure variability has often been regarded as a nuisance in attempts to find relationships between exposure and response, or differences in exposure between conditions or groups. In the present thesis, however, the focus was on reporting the sizes of variability in mechanical exposure and the possible usage and interpretation of these results in an ergonomic context.

One important use of exposure variability data is in the design of studies with an appropriate power. The statistical precision of exposure estimates depends critically on the size and sources of exposure variability within and between subjects (Allread et al., 2000; Burdorf, 1995; Burdorf et al., 1999; van der Beek et al., 1995), but comparatively few studies have been devoted to the issue of mechanical exposure variability and interpretations in terms of guidance in study design are almost non-existent (Aarås et al., 1996; Allread et al., 2000; Balogh et al., 1999; Granata et al., 1999; Hammarskjöld et al., 1990; Hansson et al., 2000; Veiersted, 1996).

1.8 Aims

The overall aim of this licentiate thesis was to explore and apply measures of mechanical exposure variability in assembly work operations.

The specific aims were:

- to explore the sizes of mechanical exposure variability in a strictly controlled, well-defined work task (study I) and in less controlled cyclic light assembly work tasks (study II).
- to apply exposure variability data statistically in the description of tasks and jobs (study I and II) as well as in the design of ergonomic intervention studies (study I).
- to interpret exposure variability data as sources of ergonomic information in tasks and jobs (study I and II).
- to apply and investigate changes in exposure variability data due to work enlargement (study I and II).

2. Material and methods

2.1 Subjects

Study I included seven subjects and study II five subjects. The background data of the subjects participating are summarised in table 1.

Table 1. Subject characteristics of the two studies, vehicle assembly work and electronics assembly work presented in means and ranges.

Study	Vehicle assembly (study I)		Electronics assembly (study II)	
	Mean	Range	Mean	Range
Gender	♀ 2 ♂ 5		♀ 3 ♂ 2	
Age (years)	35	25-52	27	23-42
Height (cm)	173	160-183	171	157-182
Weight (kg)	80	59-95	66	50-88
Experience (years)	8.5	0.7-18.8	2.2	1-4

2.2 Work procedures in the investigated tasks

Assembly task in study I

Study I was conducted in the industrial laboratory of a small automotive plant. The experimental task consisted of securing threaded fasteners with a pneumatic nutrunner, which is a commonly used tool in vehicle assembly. The joints were placed on a manoeuvrable rack (ErgoControl, Sweden) in one of three locations, which were chosen to simulate typical conditions in the industrial workshop. The three locations were called inside, upside and outside (figure 3). Two common tools were used, both about 50 cm long. One was a right-angled nutrunner weighing 3.5 kg with a mechanical clutch set at 85 Nm. The other, which weighed 4.7 kg, was equipped with a pistol grip and a reaction bar, and shut off by means of a stall type mechanism at a torque of 160 Nm. In each of the six combinations of the three joint locations and two tools, ten joints were secured in a sequence lasting about 200 s. This sequence was repeated after three minutes of rest. Thus, each subject performed in all 120 securings.

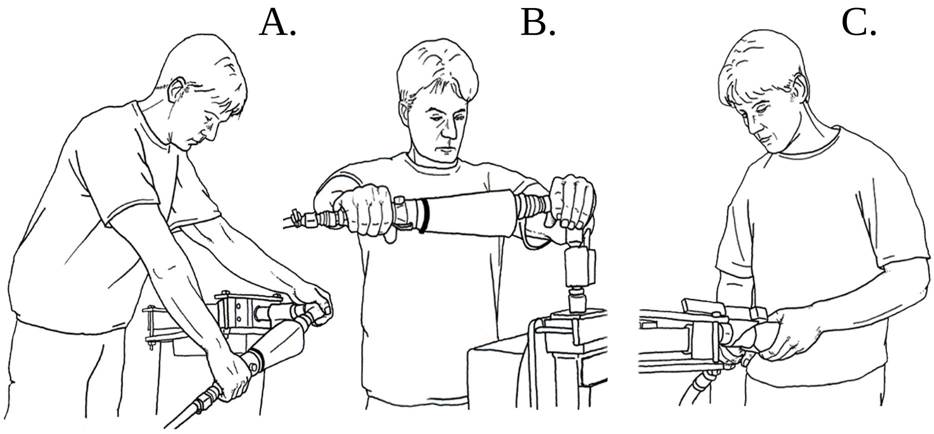

Figure 3. The assembly task performed with the same tool in the three locations in study I.

Assembly task in study II

This assembly plant produced electronic components for the automotive industry. The product of the production system in focus was instrument panels for trucks. The system comprised six workstations, which the operator rotated between during the day of assessments in order to include all the work tasks. Thus, approximately one hour of assessments was made at each workstation for each operator. Since the aim was to study variability between cycle exposures, the three workstations, which contained well-defined work cycles, were selected for further analysis. Cycle time was defined as the time required to complete one module and lasted about 3 1/2 minutes. The selected workstations involved light electronic assembling, testing and packaging operations. The work was performed seated at two workstations, *a* and *b*, (figure 4) and standing at one workstation *c*.

Figure 4. Light electronic assembly work at one of the assembly workstations.

2.3 Data acquisition

Assessments by video recordings

Continuous video recordings were made during the whole experiment in study I, as well as during the whole day of work at the electronic assembly plant. The video recordings of the experimental task were made supervisory and enabled error detection. In the electronic assembly, recordings were made at an angle obliquely from behind, in order to capture both production and postures and movements of the hands, arms and head. These recordings were primarily used to distinguish work cycles from each other, but also to detect cycles that included moments not belonging to the actual work cycle. These cycles were not included in further analyses.

Assessments by electromyography

Surface electromyography (EMG) was used to assess muscular activity during work tasks. Electromyography (EMG) was collected bilaterally from the descending part of the upper trapezius muscle and from the forearm extensors (figure 5). On each location, the skin was cleansed with alcohol and rubbed with fine emery cloth, and two disposable Ag-AgCl electrodes (Medicotest A/S, type E-05-VS, Ølstykke, Denmark) were placed along the direction of the muscle fibres with a centre-to-centre distance of 2 cm. The centre of the upper trapezius electrode pair was positioned 2 cm lateral to the mid-point of the line connecting vertebra C7 and the acromion (Mathiassen et al., 1995b). The forearm extensor electrodes were placed at one third of the distance from the lateral epicondyle to the ulnar styloid processus (Åkesson et al., 1997). The electrode impedance was measured at 25 Hz. If it exceeded 10 kΩ, electrodes were replaced after renewed preparation. The EMG signals were preamplified close to the electrodes and telemetrically transmitted to a central receiver (MESPEC 4000, MEGA electronics, Finland) in the experimental study (study I), while they were stored onto data loggers in the electronic assembly plant (study II). These data loggers were based on exchangeable flash memory cards, which enabled whole day recordings of mechanical exposure in actual work (Asterland et al., 1996).

In both studies, the obtained EMG recordings were normalised in terms of the amplitude during sub-maximal reference contractions made prior to the experiment and the actual assembly work. The RVE-procedure consisted of a reference contraction for the upper trapezius, which was to hold both arms straight and horizontal in 90° abduction while seated (Mathiassen et al., 1995b). The RVE of the lower arm extensors was obtained by applying a 1 kg load in a strap over the knuckles of the pronated hand, while the subject was seated with the lower arm resting on a horizontal tabletop. All reference contractions lasted for15 s and were performed four times. The RMS-EMG amplitude of the middle 10 s of all four appropriate recordings was then used as the reference activity (1 RVE) for each particular muscle. The RVEs of the trapezius muscles and the forearm extensors were all estimated to correspond to about 15 percent of maximal activation, MVE, on the basis of data provided by Bao and co-workers (1995) and Åkesson and co-workers (1997).

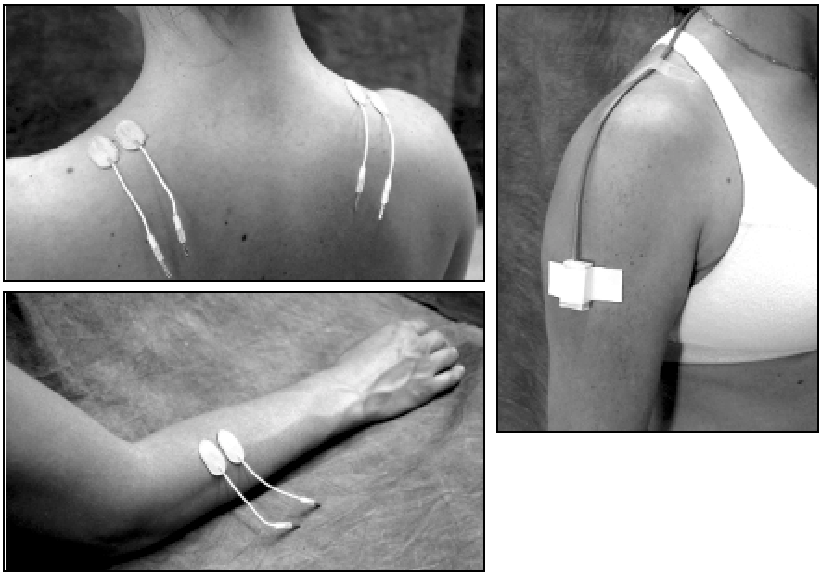

Figure 5. The location for EMG assessments from the trapezius (upper left photo) and the forearm extensors (lower left photo) and inclinometry assessments from the right arm (photo to the right).

Assessments by inclinometry

Inclinometers were applied to evaluate postures during the work tasks. The posture of the arms and head relative to the line of gravity were assessed by means of triaxial accelerometers (Åkesson et al., 1997). Calibrations of the inclinometers were made according to procedures described by Åkesson and co-workers (Åkesson et al., 1997). Two of the inclinometers were mounted using double-sided adhesive tape on the lateral part of the right and left upper arms, respectively, with the top of the inclinometer just anterior of the distal deltoid insertion (figure 5). The third was placed in the centre of the forehead. The reference posture (0°) for the arms was defined as the recording when the arm was hanging down freely over the back support of a chair with a 1-kg load in the hand. The reference position (0°) for the head was standing upright, while looking straight ahead. The inclinometry data were sampled at 20 Hz and stored on PCMCIAA cards, using data loggers (Asterland et al., 1996). The data provided by the inclinometers was then converted into the angle of inclination by software.

Synchronisation of exposure data to video recordings

Video recordings were utilised to distinguish work tasks from each other and facilitate analysis of task exposures but also for evaluation of the production system regarding e.g. productivity (Videolys; Engström et al., 1997). The integrated data of muscle activity and postures enabled ergonomic evaluation of various task exposures defined by the production system. A remote-control unit was used to mark samples on the flash memory card and simultaneously beam a light-emitting diode, which was registered by the video. During the time coding of the video recordings, this information was applied in order to digitally synchronise the video recordings with the exposure measurements (Forsman et al., submitted).

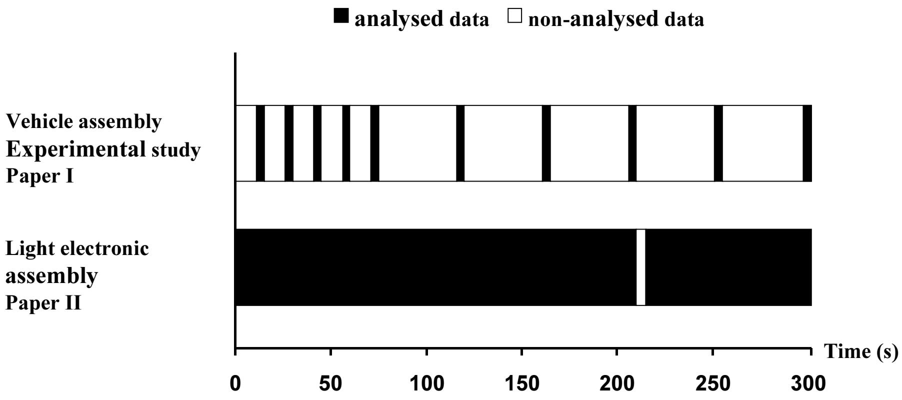

Figure 6. The analysed exposure data was the securing sequences of 4 s in study I, and the work cycles on average lasting 210 s in study II.

2.4 Data analyses

Exposure variables
Study I
The analysis was concentrated on the mechanical exposure during the 4 s of securing preceding the shut-off mechanism of the nutrunner (figure 6). The purpose was to extract data representing a repeated work task with a strictly controlled external exposure, which was determined by the joint location and the tool. For each securing, the exposure level was obtained in the form of median values of normalised EMG amplitude from the four monitored muscles: right and left upper trapezius and right and left forearm extensors, as well as median values of inclination from the three monitored body parts: head, right and left arm.

Study II
The exposure level and exposure frequency was quantified for the four muscles and three postures of each work cycle, which lasted about 200 s (figure 6). The exposure variation method (EVA), which calculates the percentage of work time spent in certain exposure level categories and time period categories was used to analyse both exposure level and exposure frequency (Mathiassen & Winkel, 1991) (figure 7). On the basis of the EVA, the exposure level for muscle activity was expressed as relative cycle time with an EMG amplitude higher than 20 % RVE. For the postures, the exposure level was quantified as relative time spent more than 30° inclined. For muscle activity as well as postures, frequency was expressed as the percentage of time spent in periods shorter than 1 s within the same exposure category.

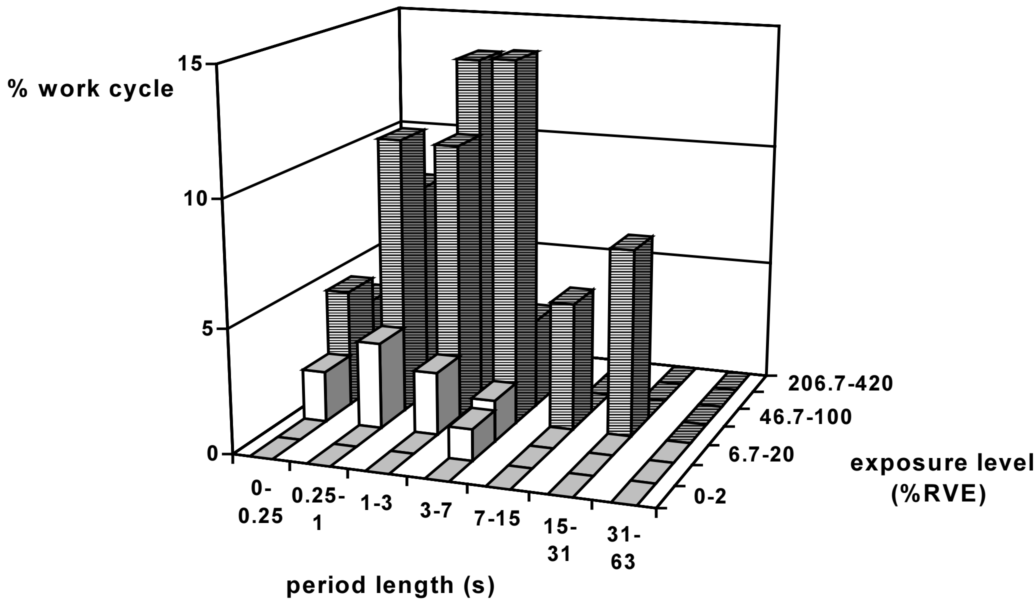

Figure 7. Diagram of an Exposure Variation Analysis (EVA). The shaded bars in this EVA illustrate the variable used to quantify exposure level of EMG amplitude data in study II, i.e. the proportion of time spent above 20 % RVE.

Statistical analysis

Study I

For each securing, the median values of inclinations for head and upper arms and normalised EMG amplitudes from the four monitored muscles were obtained. The variance components were derived by equating observed mean squared deviations with their expected values according to ANOVA algorithms for balanced, crossed (block) designs (Searle et al., 1992). For each of the seven exposure variables, ANOVAs were performed within each individual, as well as for data pooled across individuals, to derive variance components related to joint location and tool (fixed effects), and subject (random effect). An example is shown in table 2. The variability of the fixed effects and their interactions was described in terms of the mean squared error (α^2), since they are not stochastic variables. Variability within and between subjects was expressed by variance (s^2). In order to facilitate comparisons among exposure variables, exposure variability was expressed in terms of the coefficient of variation (CV), i.e. the standard deviation (SD, square root of the variance) divided by the mean (*m*). In the case of overall variability between subjects - including within-subject contributions - the CV is defined by:

$$CV_S = m^{-1} \cdot (s^2_S + s^2_{WD}/n_q)^{1/2}$$

Also, ANOVAs were performed for data pooled across tool and/or joint location in order to obtain exposure variability data for work characterised by different combinations of these two factors. For all ANOVAs, mean squared deviations were obtained using commercial software (Statistica 4.1™, Stat Soft, Tulsa OK), while variance components were derived using algorithms implemented in Excel 5.0™ (Microsoft, Redmond, WA).

Table 2. Three-way ANOVA including the effects of joint location, tool, and subject. Numbers apply to the investigated design involving 3 locations, 2 tools, 7 subjects, and 20 repetitions of every combination of location, tool, and subject.

Source of variability	df	Expected mean squared deviation
Location (L)	2	$s^2_{r\|LTS}+40s^2_{LS}+420\alpha^2_{L}$
Tool (T)	1	$s^2_{r\|LTS}+60s^2_{TS}+840\alpha^2_{T}$
Subject (S)	6	$s^2_{r\|LTS}+120s^2_{S}$
Interaction L·T	2	$s^2_{r\|LTS}+20s^2_{LTS}+420\alpha^2_{LT}$
Interaction L·S	12	$s^2_{r\|LTS}+40s^2_{LS}$
Interaction T·S	6	$s^2_{r\|LTS}+60s^2_{TS}$
Interaction L·T·S	12	$s^2_{r\|LTS}+20s^2_{LTS}$
Residual within LTS	798	$s^2_{r\|LTS}$

α^2_{L}, α^2_{T}, α^2_{LT} : mean squared error corresponding to the fixed main effects of joint location (L) and tool (T), as well as their interaction (LT)

s^2_{S}, s^2_{LS}, s^2_{TS}, s^2_{LTS} : variances corresponding to the effect of subject-days (S), interactions between joint location and subject (LS), between tool and subject (TS), and between location, tool and subject (LTS)

$s^2_{r|LTS}$: residual variance accounting for the effects of location, tool and subject

Study II

ANOVA was used to test the differences between the values of each exposure variable from every work cycle. This was performed on balanced data from the three workstations separately, and for the three combined (*a*+*b*+*c*), i.e. for each operator, the same number of work cycles was included from each workstation as determined by the smallest available number from either of the three stations. Variance within subjects, s^2_{WD}, as well as between subject-days, s^2_{S}, was estimated from the ANOVA. The variance between subject-days contains components associated with the 'true' variance between subject means, as well as the variance within subject between days. These components could not be separated as data was only collected during one day per subject.

3. Results

3.1 Average exposures

The exposure level was analysed in terms of median values of muscle activation and posture in the experimental study (study I). In study II, all three exposure dimensions were analysed: *duration* in terms of cycle time, exposure *level* in terms of proportion of cycle time with a muscle activation or posture above a certain level and exposure *frequency* in terms of proportion of cycle time with a muscle activation or posture spent in periods shorter than 1 s within the same exposure category.

Securing of joints in a mix of locations implied a median right trapezius activation of 73 % RVE, which is approximately 11 % MVE. Corresponding levels for the left trapezius, the right and the left forearm extensors were about 7 % MVE, 38 % MVE, and 30 % MVE, respectively. The median elevation for right and left upper arms was about 45°, while the median head inclination was slightly more than 30°.

In the electronics assembly study, the average cycle time across operators for the three workstations was 216 s. The overall average level of activation above 3 % MVE was 65 % of the time for the right trapezius and 69 % of the time for the left, which were lower than the levels for the forearm extensors of 86 % and 77 % of the time, respectively. Regarding posture, the average time spent in an arm posture larger than 30°, was 39 % of the time for the right arm and 36 % of the time for the left arm. Furthermore, the average head posture was 70 % of the time. The mean value for the frequency of trapezius EMG was approx 40 % of the time and for the extensor EMG approx 60 % of the time. All posture frequencies were on average approx 20 % of the time.

3.2 Mechanical exposure variability

The data on mechanical exposure variability was presented as variance components and as coefficients of variance (CV).

Study I

The 3-way ANOVA showed that joint location influenced exposure considerably, both as regards inclinations and EMG amplitudes. In contrast, the tool used had in general a marginal effect on exposure with the possible exception of the extensor muscles in the right forearm. The variability between subject-days was large, both in mean exposures across all combinations of location and tool, and in the sense that subjects reacted differently to changes in joint location. Some heterogeneity was also found between subjects as regards the response to changes in tool, in particular on the left, supportive side of the body. As expected, the within-day variability increased gradually for all variables from the restricted situation of performing securings in a specified location with a specified tool ($s^2_{r|LTS}$), to using both tools in a specified location ($s^2_{r|LS}$), to securings in an equal mix of both tools in all three locations ($s^2_{r|S}$). The sizes of the gradients reflect the influence of tool and location, respectively, and the observed values confirmed that location was a more important source of exposure variability than tool.

Study II

The variance component between subject-days (s^2_S) was larger than variance within days (s^2_{WD}) for the *duration* parameter in workstations *b* and *c*, as well as for the combination *a+b+c*. However, in workstation *a*, the opposite relationship appeared; the variance between cycles was larger than between operators. The higher value of s^2_S found in workstation *b* was probably due to the fact that two operators assembled a different version of product than the other three.

The s^2_{WD} was smaller than s^2_S for the values on trapezius activity *level* and for most posture levels, while the opposite trend, s^2_{WD} larger than s^2_S, was applicable to most measures of the extensor muscles.

The *frequency* of left trapezius activity varied more between cycles than between operators, while the two variance estimates were more alike for the right trapezius. The s^2_{WD} was lower than s^2_S for most extensor frequency values. The s^2_{WD} was larger than s^2_S for the arm postures, while the trend was not as clear for the frequencies of shifts in head posture.

Most variance estimates were lower for the frequency variables compared to the corresponding exposure level variables. This was true for both the muscle activity and the posture measures.

The relative size of exposure variability between subjects was substantially larger for EMG amplitudes on the left side of the body than for any other exposure variable (figure 8). This implies that a larger measurement effort is required to arrive at a certain precision of the group mean (table 3, n_{s1}), as well as to secure an acceptable power of a new study designed to document exposure with a specified confidence (table 3, n_{s3}). Even the ratio of within-day to between-subject-days variance differed considerably among exposure variables, resulting in different trade-offs between number of subject-days and number of recordings per day. Thus, in the case of right trapezius EMG, one additional subject was required to counteract a 90 per cent decrease in the measurement effort per subject, while seven subjects would be needed in assessments of EMG from the left forearm extensors (table 3, n_{s2}).

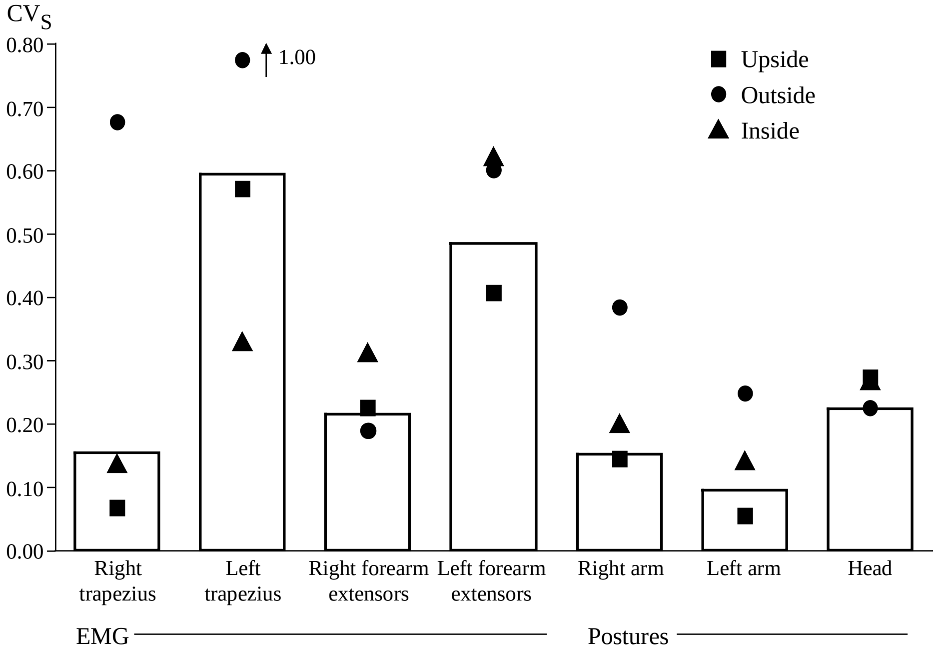

Figure 8. Coefficient of variation between subject-days, CV_s, based on the investigated exposure variables. Squares, circles, triangles represent the variability within each of the three joint locations as specified. Bars represent the variability associated with securing of joints in a mix of all three locations.

Table 3. Necessary number of subjects for obtaining specified precision and power, as well as trade-off between number of subjects and number of recordings per subject (see table footer)

	EMG				Posture		
	Right trapezius	Left trapezius	Right arm extensors	Left arm extensors	Right arm	Left arm	Head
n_{s1}	12	138	20	92	12	6	22
n_{s2}	13	142	22	99	13	7	23
n_{s3}	15	158	25	103	15	8	26

n_{s1} : number of subjects required to obtain a 95 percent confidence interval with a half-length corresponding to 10 percent of the mean exposure level. Calculated on the basis of data from the 3-way ANOVA (120 securings, balanced allocation among tools and joint locations)

n_{s2} : number of subjects required to obtain the same precision as with n_{s1} if the number of securings per subject is decreased from 120 to 12.

n_{s3} : necessary number of subjects in a new study aiming at documenting the group mean exposure with a confidence interval of the same length as above (power 0.80). Estimates based on tables in Beal (1989), using pooled coefficients of variation between subjects (figure 8).

Distinct differences were found between individuals in the size of within-day variance, s^2_{WD} (figure 9). The variance range between individuals exceeded what could be expected from random fluctuations (figure 9). Individuals even differed in responsiveness to 'work enlargement', i.e. the transition from securings performed in a specific joint location with a specific tool ('fixfix', figure 9) through securings in a mix of tools and locations ('mixmix', figure 9). In the most responsive individual, s^2_{WD} of the right upper trapezius EMG increased 30-fold during this transition, while the least responsive subject showed an increase by a factor of 1.5.

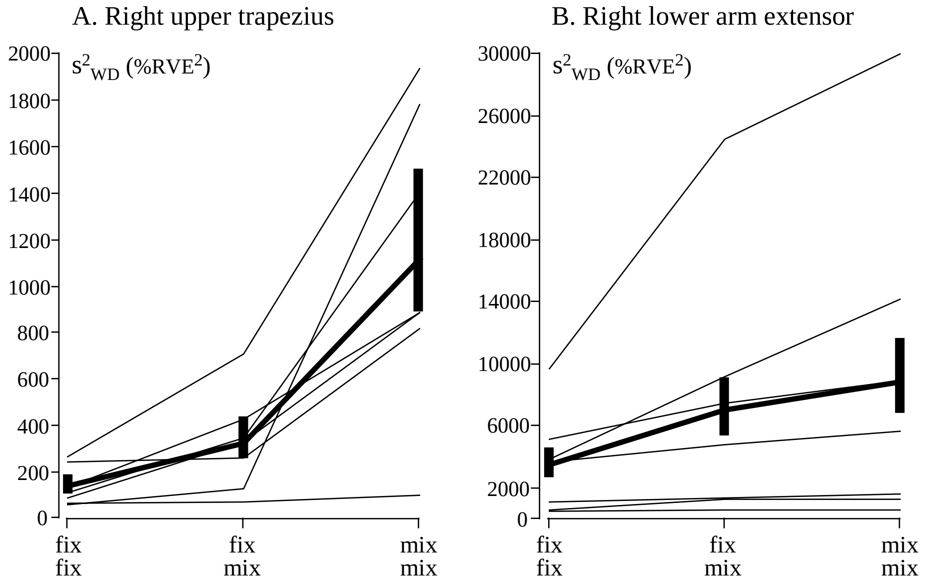

Figure 9. Within-day variance, s^2_{WD}, associated with securing of joints in a fixed location with a specified tool ('fixfix'), in a fixed location with a mix of both tools ('fixmix'), and in a mix of all three locations using both tools ('mixmix'). Results from right upper trapezius EMG (figure 9A), and right lower arm extensor EMG (figure 9B). Thin lines: individual results (n=7); Bold line: mean value; Bars: 95 per cent confidence intervals on an individual variance of the same size as the mean.

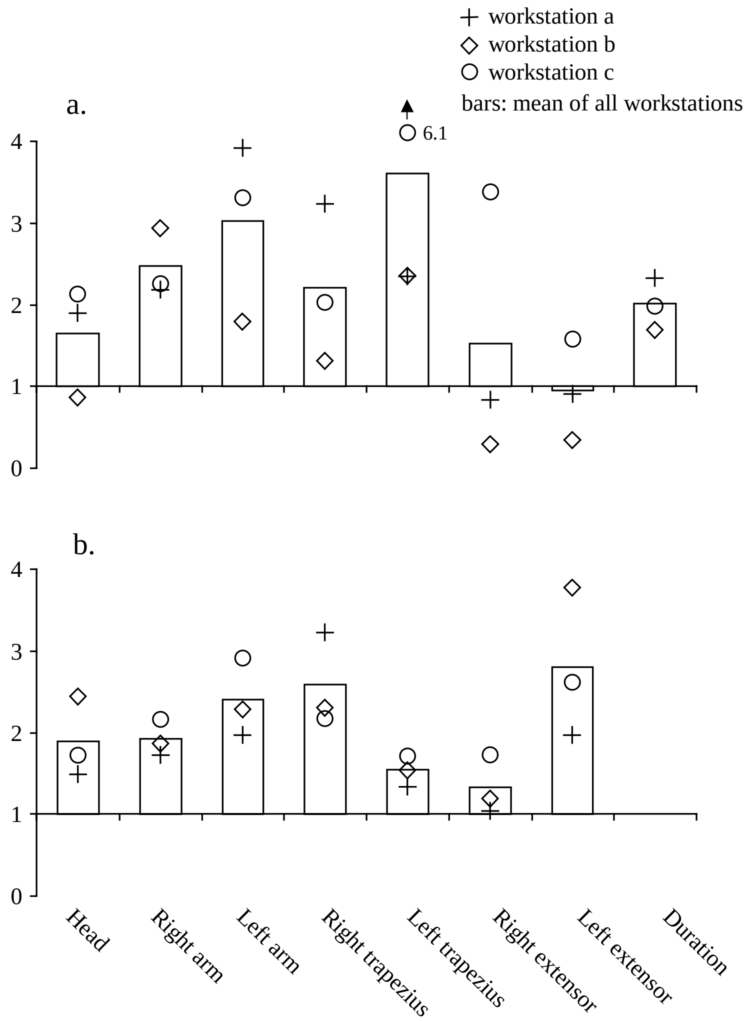

Figure 10. The effect of job rotation on exposure variability within subjects. Data is presented on exposure levels (a) and frequencies (b), separately. Symbols illustrate the effect of going from a single workstation, as indicated by the symbol, to a mix of all three stations. The effect is measured in fractions of the single-station variance. Bars indicate the mean effect across stations.

In figure 10 the relative change in within-day variance from working at a single workstation to mixing the three workstations is illustrated for exposure level and frequency in muscle activity and posture. As an example, the variance of right arm exposure level increased by a factor of 2.9 when going from work at station *b* only to work in a balanced mix of all three stations. On average, job rotation increased within-day variance for this variable by a factor of 2.5. Rotation between workstations increased the mean exposure variability up to four-fold for both the level and the frequency of muscle activity and postures (figure 10). However, in some cases, job rotation implied a lower variability than working at a single station (i.e. index below 1). For the activity level of left extensor muscles, even the average trend was a reduced variability.

4. Discussion

4.1 Variability in mechanical exposure

Data on mechanical exposure variability are most often summarised as the overall standard deviation between subjects. When data are presented in diagrams, they may only be interpreted with considerable uncertainty and make partitioning of the variability into the between- and within-subject components impossible. Figure 8 shows the overall coefficient of variation between subjects, CV_s of data from the experimental study and illustrates a typical descriptive diagram. CV is however, a preferable measure of variability, as it allows different exposure variables to be compared on a normalised scale, and since it has a direct bearing on the relationship between study size and statistical power (Beal, 1989; Cohen, 1988).

The upper right trapezius has been assessed in a considerable number of studies on manual handling tasks. The CV_s of 0.15 observed in the nutrunning task was small compared to results from e.g. light assembly work (CV_s 0.26; (Mathiassen et al., 1996), electronics assembly work (CV_s about 0.70; (Christensen, 1986) and mixed manual work (CV_s about 1.30; (Vasseljen et al., 1995). Although a number of methodological factors may influence the CV_s (Mathiassen et al., submitted), the major explanation for this large range of values is probably the different character of the investigated work tasks or jobs. Thus, a continuum appears from controlled studies of specific work tasks in the laboratory, like the task in study I (Hammarskjöld et al., 1990; Mathiassen & Winkel, 1996), through assessments of short, well-defined tasks in the field, like the ones in study II (Balogh et al., 1999), to investigations of mixed tasks (Christensen, 1986), mixed tasks including breaks (Milerad et al., 1991) and finally mixing of occupations (Vasseljen et al., 1995).

In contrast to the relatively small CV_s of the right trapezius, the observed value of 0.59 for the left trapezius (figure 8) can be found in the middle among reports in the literature. A difference in EMG variability between sides of the body was confirmed by the results from the forearms (figure 8), and a tentative explanation may be that the task of manoeuvring the nutrunner with the right arm is more constrained than that of supporting the tool.

Few previous studies have employed direct technical recordings of upper arm and head postures. Values on CV_s reported in study I (figure 8) are in general smaller than those present in the literature i.e. the CV_s for the right arm was 0.15 and for the head 0.22, compared to CV_s of about 0.7 and 0.5, respectively, in a study of cable assembly (Aarås et al., 1988). Åkesson and co-authors reported CV_s of 0.20 in head inclination in a study of dentistry (Åkesson et al., 1997). The small number of studies on the left forearm EMG and the left arm posture, found in the literature, does not justify comparisons.

Variability within days

As expected, the within-day variance s^2_{WD} increased when the securing work task (study I) was enlarged, first by allowing both tools to be used in a specific location and further by mixing locations and tools (figure 9). The mean values of s^2_{WD} obtained from the right trapezius EMG (figure 9A) correspond to CV_{WD} values of 0.16, 0.25, and 0.46 in the three conditions, respectively, while the corresponding CV_{WD} for the right extensor EMG (figure 9B) were 0.23, 0.33, and 0.37. An increase in within-day variance was also found when going from working at one workstation to rotating between the three workstations in the electronic assembly (figure 10). The mean values of s^2_{WD} increased up to fourfold, however there were large differences between exposure variables and the variability even slightly decreased for one variable: left extensor EMG (figure 10A).

Veiersted and Bao and co-workers reported substantial differences between individuals in the size of the CV_{WD}, which is in agreement with the findings in study I (Bao et al., 1995; Veiersted, 1991). Hence, the average CV_{WD} of 0.16 and 0.23, for the right trapezius and the right extensor EMG in the case of fixed tool and location were surprisingly small compared to the even more stereotypical task of abducting the arms in a specified position. One explanation may be that the assumption of independent 4-second samples is not justified, and thereby the variability may be smaller than if samples were independent.

In study II, the CV_{WD} was larger for all levels and most frequencies of trapezius-EMG compared to corresponding extensor values. This was also true for the CV_S.

To our knowledge there is no data of within-day variability in cyclically repeated tasks for head and upper arm postures are absent in the ergonomic literature. Studies by Kjellberg and co-workers (Kjellberg et al., 1998) and Granata and co-workers (Granata et al., 1999) have revealed that a controlled lifting task can be repeated with a CV_{WD} on trunk displacement of about 0.05. Much larger values of CV_{WD}, in the range from 0.40 to 1.40, were reported in a study of repeated checking operations in a supermarket, however on the basis of an expert rating of wrist and back postures (Harber et al., 1992). Hence, the CV_{WD} of postures in study I, with the range of 0.10 to 0.14 in the fixed-tool-fixed-location case, indicate that the securing task allowed for some flexibility in individual motor strategies.

Variability between subjects

As mentioned before, the accurate variance between individual mean exposures cannot be obtained in studies collecting data during only one day per subject. The ‘between-subjects variance’ observed in this design will contain a contribution of variability between days, within subjects. Ignorance of this fact may lead to incorrect interpretations of exposure variability data (Balogh et al., 1999; Kilbom & Persson, 1987). Previous studies of day-to-day variability in specific tasks propose that the between-days variance component is negligible for postures (Burdorf et al., 1994), but extensive for EMG variables (Mathiassen et al., submitted; Veiersted, 1991). This is probably due to EMG being more contaminated by methodological variability. The finding of generally lower CV_S

on postures than on EMG amplitudes in the experimental study (study I) may in part reflect these methodological differences (figure 8). However, the values of CV_S in study II, were similar and in some cases larger for the inclinometry compared to the EMG variables. This may be due to the significance of the denominator size for the CV (i.e. the mean exposure). The exposure was selected to represent the proportion of time *above* 30° or the proportion of time spent in short periods in the specified posture intervals. If the inverse time proportion had been selected, i.e. percentage time *below* 30°, the denominator and CV would radically change in this set of data, considering that the standard deviation value in the numerator does not change by this operation. The choice of posture above or below 30 degrees determines the size of CVs completely. When handling data based on expressions of proportions of time, as EVA-data is, the choice of categorisation and choice of what proportion to present also has a great impact.

A few studies have used EVA to evaluate exposure data e g (Bao et al., 1996; Hägg et al., 1997; Jensen et al., 1999; Mathiassen & Winkel, 1996). Variability of these data has not been reported; therefore comparisons of data in study II were impossible and variables could only be compared with each other.

4.2 Mechanical exposure variability as a source of ergonomic information

As discussed earlier, data on exposure variability is a necessary tool for interpreting and designing ergonomic studies. In this context, high variability is often perceived as a nuisance, since it is implied that extended resources are needed to secure an acceptable probability of success. However, as suggested below, exposure variability may in itself convey important ergonomic information concerning the characteristics of analysed work tasks or jobs, as well as information on the performance of the studied workers.

Variability within days

Using s^2_{WD} as an index of sameness is not restricted to only cyclical, consecutive tasks or operations, but may also be applied to any set of within-day samples of exposure. However, since the size of s^2_{WD} is sensitive both to the duration of the sampling period and to cyclical elements in the work (Cochran, 1977), information on these factors is needed in order to compare results from different studies. As shown in study I, s^2_{WD} may differ significantly between subjects performing the same task or combination of tasks. This suggests that the average size of the s^2_{WD} may be used as a general measure of within-day variation in subjects performing a specific work task or job, while one individual's value of s^2_{WD} reflects the variation in exposure experienced by the particular operator. The individual s^2_{WD} will also reflect the opportunity for variation offered by the task or job as well as the flexibility in the operator's motor performance strategies. The ability to vary motor performance may be an important determinant of the risk for the individual to develop disorders (Kilbom & Persson, 1987; van Dieën et al., 1993; Veiersted, 1994).

Variability between subjects
If used at the level of specific tasks, exposure variability between days, s^2_{BD}, may mainly reflect the methodological sources of variance, and therefore be of minor ergonomic interest. However, at the level of entire working days, the day-to-day variability measures the similarity in job content and exposure over days. The between-days variability was not accessible in either of the studies in this thesis, and very few, if any, ergonomic studies have so far attempted to assess whole day exposures across multiple days using direct technical recordings. The explicit exposure variability between subjects, s^2_{BS}, adjusted for between-days contributions, measures the difference in mean exposure between individuals. Thus, at task level, the s^2_{BS} reveals the extent to which individuals may employ different motor strategies / work techniques, when performing a specific task. The s^2_{BS} may increase due to the presence of certain task restrictions, for instance non-adjustable workstations, while other restrictions may be expected to decrease between-subjects variability, for instance standardised task descriptions. On the job level, s^2_{BS} will also include effects of the work organisation i.e. different work roles lead to different proportions of work tasks for each operator. s^2_{BS} will then be a measure of job exposure similarity. Obviously, a production system comprising tasks with highly differing exposures will have a potential to create jobs offering large within-subject variation as well as large differences between job exposures.

The discussion above has been focused on interpretations of within- and between-subjects variability of exposure, while contrasts between tasks and their interactions with subjects have been left unattended. The reason is that this information becomes redundant from an ergonomic point of view if data on within- and between-subjects variances are present.

Altogether, the values of within- and between-subjects variance components could be transformed into indices informing on the capability of variability in exposures in investigated tasks or jobs. The concept ‘exposure latitude’ has previously been proposed to describe this capability on the production system level (Mathiassen et al., 1997). Thus, exposure variability data may be important elements to operationalise a measure of exposure latitude. Measures of ergonomic quality in entire production systems are needed in order to adapt ergonomic intervention research to proactive analysis of planned production in co-operation with company stakeholders (Petersson et al., 2000; Winkel et al., 1999)

4.3 Mechanical exposure variability in the design of measurement strategies

The exposure variability data in study I was applied to develop measurement strategies. The required number of subjects to obtain an acceptable precision in group mean exposure varied a great deal among the investigated exposure variables and was often considerably larger in relation to general measurement efforts in ergonomic studies using direct technical methods (table 3). In the *a posteriori* as well as in the *a priori* approach, the trade-off between study size and precision is directly related to the size of the CV_S. CV_S differs substantially between joint locations (figure 8) and thereby results in a range of required study size from five subjects (right trapezius, Upside) to 380 subjects (left trapezius, Outside) if the group mean is to be determined within ± 10 per cent of its 'true' value (95 percent c.i., *a posteriori* approach).

Better precision may be obtained by increasing either the number of subjects or the number of recordings per subject. The study design only allowed for considerations regarding the trade-off between subjects on one hand and the number of securings for each subject on the other. The values of n_{s1} and n_{s2} in table 3 indicate that the number of subjects was far more important for precision than the number of recorded securings per subject.

The difference in precision between exposure variables has important implications for the design and interpretation of studies assessing exposure with multiple methods. One suggestion to alleviate this problem would be to design studies on the basis of exposure variability information so that their ability to detect intervention effects would be approximately equal for all applied exposure variables. This would require that different amounts of data were collected for different variables, for instance by using study populations of different sizes.

4.4 Mechanical exposure variability in the context of ergonomic interventions

As monotonous, repetitive work has been found to increase the risk for developing musculoskeletal disorders, ergonomic interventions should be concentrated on decreasing monotony and repetitive work patterns, by increasing the variation in the work task/ job. Very few epidemiological studies have specifically focused on the effect of variation. In a study by Roquelaure and co-authors, the risk of contracting a carpal tunnel syndrome was 6.3 times higher for manufacturing jobs with no job rotation, compared to a reference group (Roquelaure et al., 1997). In a case-control-study of manual and office workers it was found that the cases among the manual workers were less satisfied with the variation in workload compared with a control group and the group of office workers (Vasseljen et al., 1995). However, a number of studies show indirectly that varying work is associated with less risk than work with few and similar work tasks e.g. in the fish processing industry (Ohlsson et al., 1994), during computer work (Bergqvist et al., 1995) and during assembly work (Kadefors et al., 1996). Less variability has been found in computerised work tasks compared to manual tasks (Waersted et al., 1997). The same may be true for the automation of assembly work tasks compared to manual assembly. Trends in modern working life point to increased occurrence of high-paced and automated tasks, often in close association with computers. These trends might lead to lower exposure variability.

Variation may be created by job enlargement such as enlargement of the task, which in this thesis is exemplified by performing the nutrunning task in three different locations using two different tools instead of one location and one tool. The enlargement of the nutrunning task increased the within subject variability for the right trapezius by approximately five times and approximately doubled the variability for the right forearm extensor (figure 9). Study II exemplifies job enlargement by rotation between work tasks, which conveyed working in three workstations compared to one. This resulted in variability changes from almost nil up to four times larger variance compared to working at a single workstation. Variability was expected to increase, but the size of the effect was not known before. Additional studies of other job rotation schedules, involving different tasks in different proportions, will provide a reference for evaluating the size of the variance increase found here. According to common ergonomic concepts, effective job rotation schedules require tasks that differ in exposure level and frequency. If the available work tasks in a job rotation schedule are more different in terms of exposure level, frequency and duration, the exposure variability in the entire job will also increase. As an example, if a workstation with manual handling of heavy material were added to the electronics assembly work in study II, job rotation would most probably result in a larger increase in exposure variability than what was found with the present rotation. In contrast, adding administrative computerized work tasks into the job rotation scheme may be of little effect since the exposure in keyboarding tasks is similar to assembly work. On the other hand, adding administrative work tasks to industrial work may have other effects than those on mechanical exposure, which may be at least as important: increased mental variation and enhancement of skills. Mental variation could not be reflected on by the operational measure of variability used in this study, but probably has effects on the perception of monotony in work tasks.

Implementation of successful job rotation schemes is complex, involving both mechanical as well as psychosocial aspects. Christmansson and co-workers found an increase in occurrence of musculoskeletal disorders to be the result of an intervention towards an increased array of available work tasks, and explained this unexpected finding by bad psychosocial work conditions and lack of skill and competence among the work force at the plant (Christmansson et al., 1999). This shows that the procedure for implementing a job rotation scheme is a critical factor for the realisation of potential benefits (Vezina et al., 1999). It has been shown that participatory approaches, including problem solving by those who have first-hand experience, may be effective and feasible in order to reduce workload and increase job satisfaction (Kourinka, 1997; Pohjonen et al., 1998), and this may well apply even to the implementation of job rotation.

4.5 Future research

There is a need to obtain more data on exposure variability in other work tasks and jobs, in order to make adequate comparisons of the size of variability in different work tasks and study the impact of degrees of freedom in the work tasks. A measure of variability may be recognised as an important characterisation of a work task.

Laboratory studies would be necessary to investigate how variability in mechanical exposure may affect the mechanisms developing musculoskeletal disorder in tissues of interest, and thereby contribute to the definition of optimal variability. It would also be interesting to include questions on ‘lack of variation’ in both the physical and psychological sense in future epidemiological studies, in order to investigate if this could be a risk estimate of importance.

It is also necessary to follow the trends of changes in job content and their effect on variation of mechanical exposures, continuing the research into how to effectively improve the physical and mental variation in work tasks and create more appealing jobs. Future ergonomic intervention studies need to apply improved measurement strategies, as well as carefully plan and apply functioning intervention programmes.

5. Conclusions

The present studies lead to the following main conclusions:

Simple measures of exposure variability derived by ANOVA techniques showed to be promising instruments for describing similarity in mechanical exposure. Exposure variance components are suggested to represent operational measures relevant to the similarity of repeated work operations, tasks or jobs, and hence descriptions of repetitive work.

Exposure variance components are important prerequisites for designing efficient measurement strategies in ergonomic intervention studies.

Work enlargement in terms of job rotation generally increased variability in mechanical exposure measured by muscle activity and postures. The size of the increase differed between the exposure variables.

6. Summary

Möller T. *Mechanical exposure variability in industrial assembly work*. Arbete och Hälsa 2001:1.

Many industrial assembly tasks may be characterised as repetitive and monotonous, which increases the risk of developing musculoskeletal disorders, in particular in the upper limbs. Hence, an increased variation within the job, both physical and mental variation, is a common suggestion for ergonomic interventions. By applying different strategies for job enlargement e.g. job rotation it may be possible to achieve more variation, but few interventions studies have focused on the results in terms of variation. Analysis of mechanical exposure variability may facilitate the evaluation of variability in work tasks and may also function as a measure of motor flexibility and work technique. Another important purpose for analysing exposure variability data is to improve and develop more effective measurement strategies in the planning of ergonomic intervention studies.

Both studies included in this thesis are based on field studies in industrial assembly plants; however, the set-up in the first study was more of an experimental character. The assembly task in the experimental study was nutrunning in three different locations with two different tools. The work tasks in the second study predominantly involved light electronic assembling and testing in work cycles lasting approx 3 1/2 minutes. Variability was analysed by ANOVAs on the mechanical exposure data collected by electromyography and inclinometry. The exposure level was analysed in study I while both exposure level and frequency as well as duration of work cycles were analysed in study II.

The results showed that by enlarging the nutrunning task from securings with a specified location and tool to a mix of all locations and tools, the within-subject variance increased 2- to 37-fold, depending on exposure variable. Subjects differed systematically in responsiveness to this transition. The necessary number of subjects to arrive at a group mean exposure in mixed work with 95 percent confidence limits corresponding to ±10 percent of the mean ranged between 8 and 158, depending on exposure variable. Job rotation between three workstations compared to working only at one, changed the within subject variance between nil up to fourfold for the different exposure variables. Since the difference in mean exposure between workstations was larger for the trapezius EMG variables than for the extensor EMG and the postures, the effects of job rotation was larger for the trapezius. Both enlargement of the nutrunning task and job rotation increased the variation according to most of the used exposure variables; although the effects in terms of changed risk for disorders is not known. Important ergonomic effects of job enlargement may be quantified using exposure variability information. It is concluded that exposure variability may serve both as ergonomic information i.e. description of work tasks or an individual's work technique. The procedure used for incorporating exposure variability data in study design showed that statistical power is largely dependent on exposure variable and thereby useful information in the planning of new ergonomic studies, intervention as well as epidemiological studies.

Keywords: arm, EMG, electronics assembly, job rotation, job enlargement, nutrunner, posture, physical load, repetitive work, shoulder, work cycle

7. Summary in Swedish

Möller T. *Variabilitet i mekanisk exponering vid industriellt monteringsarbete.* Arbete och Hälsa 2001:1

Många industriella monteringsarbeten kan karaktäriseras som repetitiva och monotona, vilket är faktorer som ökar risken att utveckla muskuloskeletala besvär i synnerhet i de övre extremiteterna. Därför är en ökning i variationen av arbetet, både fysisk och mental variation, ett vanligt förslag för ergonomiskt förändringsarbete. Genom att tillämpa olika strategier för arbetsutvidgning, t.ex. arbetsrotation, kan en ökad variation möjligtvis åstadkommas, men få förändringsstudier har hittills fokuserat på resultaten i form av variation. Analys av mekanisk exponeringsvariabilitet kan underlätta utvärdering av variationen i olika arbetsuppgifter men kan också fungera som ett mått på individens motoriska flexibilitet samt arbetsteknik. Ett annat skäl till att analysera data på exponeringsvariabilitet är att förbättra och utveckla mer effektiva mätstrategier användbara i planeringen av nya ergonomiska förändringsstudier.

Båda studierna inkluderade i denna avhandling är baserade på fältstudier i industriella monteringsmiljöer; även om uppställningen i den första studien var mer av experimentell karaktär. Monteringsuppgiften i denna studie var mutterdragning i tre olika positioner med två olika verktyg. Arbetsuppgifterna i den andra studien dominerades av lätt elektronisk montering och testning i arbetscykler som varade ca 3 1/2 minuter. Variationen i mekanisk exponerings-data, mätt med elektromyografi och inklinometri, analyserades med hjälp av ANOVA. Exponeringsnivån analyserades i studie I medan exponeringsnivå, frekvens samt durationen av arbetscykler analyserades i studie II. Resultaten visade att utvidgning av mutterdragningsuppgiften från dragning i en specifik position med ett visst verktyg till att blanda alla positioner och verktyg medförde en ökning av inomindividsvariansen mellan 2 till 37 gånger, beroende på exponeringsvariabel. Individerna skiljde sig systematiskt åt i mottaglighet till denna förändring. Det nödvändiga antalet individer för att nå ett gruppmedelvärde för det ’blandade’ arbetet med ett 95 % konfidensintervall motsvarande ±10 procent av medelvärdet, varierade mellan 8 och 158, beroende på exponeringsvariabel. Rotation mellan de tre arbetsstationerna jämfört med att arbeta i endast en, förändrade inomindividsvariansen med noll upp till fyra gånger, beroende på exponeringsvariabel. Eftersom skillnaderna i medelexponering vid de olika arbetsstationerna var större för trapezius EMG variabler än för extensor EMG variabler och vinklar, blev effekterna av arbetsrotation större för trapezius. Både utvidgning av mutterdragningen och arbetsrotation ökade alltså variationen enligt de flesta av de använda exponeringsvariablerna; även om effekterna i förhållande till förändrad risk för besvär är okänd och de ergonomiska effekterna av arbetsutvidgning kan kvantifieras med hjälp av exponeringsvariabilitet. Exponeringsvariabilitet kan tjäna både som ergonomisk information vid beskrivning av arbetsuppgifter såväl som individens arbetsteknik. Proceduren som användes för att införliva data från exponeringsvariabilitet i studiedesignen, visade att statistisk styrka är till stor del beroende på exponeringsvariabel och därmed värdefull information vid planering av nya ergonomiska studier, såväl vid förändrings- som epidemiologiska studier.

Nyckelord: arbetscykel, arbetsrotation, arbetsställning, arbetsutvidgning, arm, elektromyografi, inklinometri, muskuloskeletal belastning, mutterdragare, repetitivt arbete, skuldra

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