Hansson, G- and Arvidsson, I and Ohlsson, K and Nordander, C and
Mathiassen, S E and Skerfving, S and Balogh, I

“Precision of measurements of physical workload during standardised manual
handling. Part II: Inclinometry of head, upper back, neck and upper arms”

J Electromyogr Kinesiol. 2005 Aug 13; [Epub ahead of print]

Publisher: Elsevier

Alternative location: http://dx.doi.org/10.1016/j.jelekin.2005.06.009

Precision of measurements of physical workload during standardised manual handling

Part II: Inclinometry of head, upper back, neck and upper arms

G.-Å. Hansson [a,*], I. Arvidsson [a], K. Ohlsson [a], C. Nordander [a], S. E. Mathiassen [b],
S. Skerfving [a], I. Balogh [a]

[a] Department of Occupational and Environmental Medicine, University Hospital,
SE-221 85 Lund, Sweden
[b] Centre for Musculoskeletal Research, University of Gävle, PO Box 7629, SE-907 12 Umeå,
Sweden

*Corresponding author. Tel.: +46 46 173185; fax: +46 46 173180.
E-mail address: gert-ake.hansson@ymed.lu.se

Style: Journal of Electromyography and Kinesiology

Abstract

For measuring the physical exposure/workload in studies of work-related musculoskeletal disorders, direct measurements are valuable. However, the between-days and between-subjects variability, as well as the precision of the method per se, are not well known.

In a laboratory, six women performed three standardized assembly tasks, all of them repeated on three different days. Triaxial inclinometers were applied to the head, upper back and upper arms. Between-days (within subjects) and between-subjects (within tasks) variance components were derived for the 10th, 50th and 90th percentiles of the angular and the angular velocity distributions, and for the proportion of time spent in predefined angular sectors.

For percentiles of the angular distributions, the average between-days variability was 3.4°, and the between-subjects variability 4.0°. For proportion of time spent in angular sectors, the variability depended on the percentage of time spent in the sector; the relative variability was scattered and large, on average 103% between days and 56% between subjects. For the angular velocity percentiles, the average between-days variability was 7.9%, and the average between-subjects variability was 22%.

The contribution of the measurement procedure per se to the between-days variability, i.e. the imprecision of the method, was small: less than 2° for angles and 3% for angular velocity.

Key words: Intra-individual; Inter-individual; Exposure variability; Assembly work

1. Introduction

Physical workload (e.g. excessive and prolonged muscular load, awkward and constrained postures, and repetitive movements) has been identified as a risk factor for developing work-related musculoskeletal disorders (WMSDs) [6,24,27]. Quantitative exposure-response relations are, however, known only to a very limited extent. This lack of knowledge hampers surveillance and regulation of these risk factors, and present standards and guidelines are often expressed in qualitative, process-oriented terms [10,11]. So far, attempts to implement these standards, guidelines, and regulations, have not led to a decrease in the occurrence of WMSDs.

Legislative regulation, analogue to threshold limit values (TLVs) for exposure to toxic chemicals, noise and vibration, might prove more successful. By using technical measurements, which show a better validity, accuracy and precision than observation methods [17,29,36,37], the scientific basis of TLVs can be improved, and compliance surveyed.

For measuring postures, uniaxial and biaxial inclinometers have been extensively used. One major advantage of inclinometry is that definitions of head, upper back, neck and upper arm postures adhere to the ISO-standard ‘Ergonomics – Evaluation of static working postures’ [15]. However, excessive errors may occur during inclination in arbitrary directions even when biaxial inclinometers are used [12]. Moreover, most inclinometers are based on transducers comprising moving parts, which limits their frequency response to a few Hz, and, hence, reduces their accuracy during dynamic conditions. To overcome these limitations we have developed triaxial accelerometers for whole-day ambulatory inclinometry [12], which have an accuracy and reproducibility that is independent of the direction and the magnitude of the inclination. They provide valid data under the dynamic conditions that occur during ordinary occupational work [7,12]. The instrumentation has been applied in studies of occupational work, e.g. [2,5,14,17,33].

When inclinometers are applied for characterising the physical workload, variability (in addition to that inherent in the instrument) will be introduced, e.g. due to the non-perfect reproducibility of the reference positions. Moreover, for a particular subject there will be between-days variability, due to actual differences in task requirements, as well as differences in work performance. In addition, different individuals will not perform the same task in an identical manner. The size of between-days and between-subjects variability are crucial for determining sampling strategies, e.g. in epidemiological studies [19,32] and for surveillance of TLVs [9,20,21,22,26].

This study is one part of a larger investigation, which also evaluated the precision of electromyography [25] and goniometry (to be published). The specific aim of the present study was to evaluate the usability of inclinometry based on triaxial accelerometers for assessing industrial tasks, in terms of precision of the method per se, as well as between-days and between-subjects variability.

2. Subjects and methods

2.1. Subjects

Six healthy, right handed, female subjects from the department staff participated in the study. Their median age was 44 (range 36-54) years, height 168 (158-173) cm, and weight 64 (58-82) kg. The Ethics Committee of Lund University approved the study, and all participants gave their written informed consent.

2.2. Work tasks

At each trial, the subjects performed three standardised work tasks in a laboratory setting. The tasks were designed to give different levels of physical exposure. The work task 'materials picking' implied collection of materials (small details as screws and wing nuts, as well as iron weights of 2.2 and 3.2 kg), for the two other tasks, transfer of the materials on carts, and downloading of the material at the workstations. 'Light assembly', assembly of table holders for desk lamps, implied handling of light objects by both hands, with an average cycle time of 24 s. 'Heavy assembly', assembly of stands for desk lamps, consisted in handling of more and heavier components with an average cycle time of 58 s. Each task was performed for about 20 minutes. For details see Nordander et al. [25].

2.3. Study design

All subjects performed at least three trials on separate days, separated by at least seven days (in addition to their first trial, which was considered to be a training occasion and therefore excluded in the analyses). Two subjects performed an additional trial, since some data in the previous trials had been lost due to technical problems. Preceding each trial, measurement equipment was applied to the subject for simultaneous measurement of muscular activity (electromyography [25]), head and upper arm movements (inclinometry, see below), and wrist movements (goniometry). In all trials, the work tasks were performed in the sequence 'materials picking', 'light assembly', 'heavy assembly'. A break of about 10 minutes was organised between the tasks.

2.4. Inclinometry

Inclinometers, based on triaxial accelerometers (Logger Teknologi HB, Åkarp, Sweden), were used to measure the angle relative to the line of gravity [12], for the head, upper back and both upper arms. Data were sampled at 20 Hz using a datalogger (Logger Teknologi HB, Åkarp, Sweden) [13]. These inclinometers do not have to be aligned with the orientation of the body segment; by recording of a reference position (defining 0° of inclination) and a position representing the forward direction, the co-ordinates can be transformed from the inclinometer to the body segment. The inclinometers per se have an accuracy of 1.3° and a reproducibility of 0.2° [12].

One inclinometer was placed on the forehead, another one to the right of the cervico-thoracic spine at the level of C7-Th1. For the upper arms, the inclinometer was fixed to a plastic plate (55×27 mm), which was placed along the upper arm, with the lateral edge along a line from the lateral-posterior corner of the acromion to the lateral epicondyle, and the upper edge at the insertion of the deltoid muscle. For the head and upper back, the forward/backward and sideways projections of the inclination angles (flexion/extension and lateral flexion below) and the absolute value of their time derivatives ($v_i=|(a_{i+1}-a_{i-1})\times 0.5\times f|$; v_i= absolute velocity for sample number i, a_{i+1}= angle value for sample number i+1, a_{i-1}= angle value for sample number i-1, f= sampling frequency) were used to describe postures and movements [2, 12]. The forward/backward and sideways bending of the neck was, for each sample, calculated as the differences between the corresponding measures for the head and the upper back; the time derivatives of these differences were also calculated, using the same algorithm as for the head and the upper back.

The reference position for the head and upper back (0° flexion/extension and 0° lateral flexion) was defined with the subject standing upright, looking at a mark at eye-level. The forward direction of the head and back was defined with the subject sitting, leaning forward, looking at the floor. For the upper arms, the elevation angle (i.e. the angle relative to the line of gravity independent of direction) was used to describe postures, and the generalised angular velocity, i.e. the time derivatives of the position on the unit sphere, were used to describe the movements [12]. The reference position (0° inclination) for the upper arms was obtained with the subject seated, with the side of the body leaning towards the armrest of the chair, and the arm hanging perpendicular over the armrest, with a 2 kg dumbbell in her hand.

The 10th, 50th and 90th percentiles of the angular and the angular velocity distributions were used for characterising postures and movements, respectively. Postures were also described by the proportion of time that angles fell in predefined sectors. For the head, the upper back and the neck, three sectors (<-15°, >15°, and >45°) were used for flexion/extension, and one (<-15° *or* >15°) for lateral flexion. For upper arm elevation, the sectors were >30°, and >60°. The software for the basic analysis is described elsewhere [12]. The calculations of neck angles and angular velocities, percentile values, and time in predefined sectors, were performed in an application written in Matlab version 6.5 (The MathWorks, Inc., Natick, MA, USA).

2.5. Statistics

For each posture and movement measure, the mean value across the measuring days was calculated for each subject, and the mean of these values formed the (group) mean value. For each task and each measure, the between days (within subjects) and between subjects variance components were derived, using a hierarchic restricted maximum likelihood algorithm in a general linear random effects model (SPSS 10.0, SPSS Inc., Chicago, IL, USA). The standard deviation (SD = square root of the variance) was used for characterizing the precision of the angular measures; its dimension is degree, and it is easy to interpret. The coefficient of variation (CV = ratio between SD and mean value) was used for the absolute velocity measures; the reason for using relative errors being that these velocity values are inherently positive, their magnitudes depend on the percentile chosen, and SD increased with the mean value.

3. Results

As intended, the three work tasks differed regarding postures. For example, the head was held in a considerably more flexed position during ‘materials picking’ (24°/41°/51° for the 10th/50th/90th percentiles, and 33% of the time flexed >45°) as compared to ‘light assembly’ (14°/23°/29° and 0.21% of the time) and ‘heavy assembly’ (13°/28°/38° and 3.7% of the time; Table 1 and 2; Fig. 1). Tasks also contrasted with respect to movements; the non-cyclic task ‘materials picking’ displayed higher velocities than the two cyclic assembly tasks for all percentiles, in general for the head, upper back and neck, and consistently for the upper arms.

3.1. Between-days variability

The plots of the individual data revealed that, for the angular measures, some subjects showed systematically deviating values for all three tasks on the same day. One example is shown in Fig. 1, where lower values for the 90th percentiles of head flexion/extension were registered for subject B for all three work tasks on day 2, as compared to days 1 and 3. For this subject and day, the same deviation was also seen for the other percentiles of the distribution (not in figure). A corresponding pattern was not seen for the velocity measures (Fig. 2).

For *head flexion/extension*, SD between days (SD_{BD}) was, on average, for the 10th, 50th and 90th percentiles and the three tasks, 3.1° (range 2.6° to 3.7°; Table 1). The SD_{BD} for the three percentiles were almost identical within each task. The differences between the tasks were also small. The SD_{BD} for the *lateral flexion of the head* was, on average, 2.0°, i.e. somewhat smaller than for flexion/extension.

For the *upper back*, the corresponding average SD_{BD} were 3.5° and 3.0° for flexion/extension and lateral flexion, respectively (Table 1). The SD_{BD} for the *neck* postures (on average 4.5° and 3.3° for flexion/extension and lateral flexion, respectively) were, in general, higher than the corresponding values for both the head and the upper back.

For both the right and left *upper arm elevation*, the SD_{BD} were lower for ‘materials picking’ than for the other two tasks, and, for this task, the SD_{BD} increased with the percentiles (on average for the right and left upper arms 1.8°/2.2°/2.8° for the 10th/50th/90th percentiles; Table 1). The highest SD_{BD} occurred for the left upper arm during ‘light assembly’, on average for the three percentiles 6.3°. SD_{BD} for upper arm elevation was, on average for both arms, all tasks and all percentiles, 3.8°.

When the postures were characterised by percent time spent in selected angular sectors, some of these sectors contained almost no (or no) observations (Table 2). For these sectors, both the mean value and the SD_{BD} became almost zero (or zero), Moreover, there was a relation between SD_{BD} and the corresponding mean values (Fig. 3a); SD_{BD} was zero at 0% time and, in general, increased with increasing mean value for mean values <50% time. To get a more comprehensive measure of the variability, i.e. a measure that is unrelated to the mean value, for data whit this characteristic, the quotient between SD and the mean value, i.e. the coefficient of variance (CV) is preferable. However, in the present data, the relation between SD and the mean value is inverted for mean values >50% time; SD decreases with increasing mean value. Thus, to get a measure of variability that reduces the strong relation to the mean value, a normalisation of the SD_{BD} to the mean value, only slightly different from the definition of CV, was performed: SD_{BD}/(min(mean, (100-mean))), i.e. the ratio between SD_{BD} and the lowest of the two figures for the mean value, and 100 minus the mean value. This normalised value was, on average, 103%, but showed highly scattered values for mean values close to 0% time (Fig. 3b).

Regarding velocities, there was a lower limit for the CV_{BD} values of 3% (Table 3). CV_{BD} was, in most of the 24 combinations of the eight distributions and the three tasks, similar for the 50th and 90th percentiles (both averaged 7.5%). For the 10th percentile, CV_{BD} was somewhat higher (8.8%); this effect was mainly caused by a higher variability in the 10th, as compared to the 50th and 90th percentiles, for the task 'materials picking'. For the head, upper back and neck, 'light assembly' showed consistently higher CV_{BD} than the other two tasks.

3.2. Between-subjects variability

Task was an important determinant for postures and movements, but there were also considerable inter-individual differences in exposure within tasks (c.f. Figs. 1 and 2). For example, all subjects held their head most flexed during 'materials picking' and least flexed during 'light assembly', however one subject (A) worked in a generally more flexed position, and another subject (F) showed small differences between the tasks (Fig. 1). Individual patterns were also seen for movements; for example, for all tasks and all trials, subjects C showed consistently lower, and subject F higher values, than the other subjects (Fig. 2).

For *head flexion/extension*, SD between subjects (SD_{BS}) were, on average, for the three tasks and the 10th, 50th and 90th percentiles, 4.5°, i.e. higher than SD_{BD} (Table 1; Fig. 1). Except for the zero value for the 10th percentile of 'heavy assembly', the variability was similar for all tasks, and increased with the percentiles. For the *lateral flexion of the head*, the SD_{BS} were on average 2.5°, i.e. somewhat higher than SD_{BD}.

For the *upper back*, the corresponding averages of SD_{BS} were 5.3° and 2.6° for flexion/extension and lateral flexion, respectively (Table 1). The SD_{BS} for the *neck* postures (on average 4.4° for flexion/extension and 3.6° for lateral flexion) were of the same size as the corresponding SD_{BD}.

For *upper arm elevation*, there was no consistent effect of side, task or percentile on the variability (Table 1). The SD_{BS} were, on average, 4.5°, which is marginally higher than SD_{BD}.

When the postures were characterised by percent time spent in selected angular sectors, SD_{BS} exhibited the same characteristics as SD_{BD} (Table 2; Fig. 3a and 3b). Hence, SD_{BS} was normalised in the same way as SD_{BD}, and, on average, this value was 56%. When comparing the variability between subjects and between days, no consistent relation was found between SD_{BS} and SD_{BD}. The higher values for the normalised between-days variability, as compared to the between-subjects variability, were mainly caused by larger SD_{BD} at mean values close to zero.

The upper arms displayed the highest *angular velocities* (Table 3). For the *right upper arm*, the between-subjects variability, CV_{BS}, was higher for ‘light assembly’ (mean for the three percentiles 33%) than for ‘heavy assembly’ (20%) and ‘materials picking’ (19%), while the velocities were similar for three tasks. In contrast, for the *left upper arm*, CV_{BS} was higher for ‘materials picking’ (45%), than for ‘light assembly’ (24%) and ‘heavy assembly’ (25%).

In general, the between-subjects variability, CV_{BS}, was, for ‘light assembly’ and ‘heavy assembly’, similar for the three percentiles, while, for ‘materials picking’, it decreased with increasing percentiles (Table 3). The average CV_{BS}, for the 72 combinations of body segments and movement directions, the three tasks, and the three percentiles, was 22%. The between-subjects variability was higher than the between-days variability; for the 72 combinations, the overall average CV_{BS}/CV_{BD} ratio was 3.2, (range 1.1 to 9.5).

4. Discussion

The tasks differed in postures and movements; however, the variability was only to a minor extent influenced by the tasks performed. For posture percentiles, the overall average variability was small (SD_{BD} 3.4°, and SD_{BS} 4.0°). Time spent in angular sectors varied more, the normalised SD_{BD} was 103%, and the normalised SD_{BS} was 56%. For angular velocities, the average variability was 7.9% for CV_{BD} and 22% for CV_{BS}.

4.1. Definition of tasks

The chosen tasks were intended to be representative for manual work, and the mean values are in accordance with similar tasks recorded during occupational work [1,5,22,23,30]. To eliminate variability caused by actual changes in task requirements, the tasks were highly standardised. Moreover, to eliminate the possible additional variability, due to different states of fatigue, caused by the performance of the preceding task, the tasks were always performed in the same order.

The extent of standardisation that was accomplished in the present study is, however, not representative for real work. One reason is that, during real assembly, the produced items usually vary during the day as well as between days [4,8,21,23]. Further, the definitions, as well as the delimiting in time, of the tasks that comprise a job, is usually less obvious than in the present study. Hence, in field studies of actual work, additional variability within tasks can be expected both between days and between subjects, and the variability derived in the present study most likely represent minimum values, which can be expected only for stereotypic tasks.

4.2. Proportion of time in specific sectors

Regarding the choice of number of *angular sectors*, as well as their limits, there are no generally accepted values, and, although the present sector limits are commonly used, a wide variety of other sector limits has been applied [16]. However, since the variation is primarily related to the fraction of time spent in a sector (and not to the sector limits per se) the results can be generalised to arbitrary sector limits. In addition to enable comparison with earlier presented data, the sectors selected in the present study aim to reflect risk, i.e. an increase in % time spent in a sector should imply an increased risk. For example, for lateral flexion, the proportion of time outside a neutral position (<-15° *or* >15°) was chosen, rather than the time spent in the neutral one. Moreover, sectors limited at both ends (e.g. upper arm elevation >30° *and* <60°) were avoided, since a decrease in the proportion of time in such sectors may imply a decreased elevation (i.e. more time spent below 30°), as well as an increased elevation (i.e. more time spent above 60°).

Time spent in a specific sector is limited to a value between 0% and 100%. If the selected sectors cover the whole range of possible positions, the values for the sectors will become complementary, i.e. the sum of the time will amount to 100%. This will introduce an ambiguity when expressing variability relative to the mean. For example, for two complementary sectors, if a person spends 99% of the time in one sector (and hence 1% in the other one) all information is provided by just one of the two figures. Moreover, the SD will (by definition) be the same for both sectors. Hence, CV will be approximately 100 times as high if SD is normalised to the sector where 1% of the time was spent, than to the complementary sector. This ambiguity was eliminated by normalising SD according to a modified definition of CV, used to provide the data in Fig. 3b. These normalised SDs showed, for between-days, as well as for between-subjects variability, high, and, for low mean values, widely scattered values. Since sectors with low mean values exhibited multiple data with zero values, and the normalisation is sensitive to the occurrences of zeroes, this fact is the likely reason for the scattering.

Proportion of time in specific sectors, as well as percentiles, are both extracted from the amplitude distribution. Still, the variability for the percentile values is, in contrast to that for proportion of time, more consistent, and basically independent of the mean value. Specifically, when comparing data using different measurement methods, the effect of a systematic method difference, can, for the percentile value, easily be compensated for by adding (or subtracting) the difference, while, for proportion of time, the compensation requires knowledge of the shape of the amplitude distribution.

4.3. Accuracy and precision of the method

Both high accuracy and high precision is required for a method with high validity. The present study design does not allow estimates of accuracy. However, in a previous study [12] the accuracy of the inclinometer and software was determined to 1.3°, and the reproducibility of the individual inclinometers to 0.2°. Considering that, during practical use, the inclinometers are interchanged between body segments and trials, the accuracy, rather than the reproducibility of the individual inclinometers, is a relevant estimate, which will not overestimate the precision of the inclinometer and software.

In addition to the error of the transducers and the software, the alignment of the transducer to the body segment, or, as for the present method, the recording of reference positions also contributes to the method error. By defining the reference positions as those obtained during standardised postures, this error will appear as imprecision and not inaccuracy. In a study of the natural head position in standing subjects, Solow and Tallgren [28] found a reproducibility of 1.4° for head flexion/extension, and similar values have been reported in another study [35]. Hence, the contribution of the method per se to the overall exposure variability can, for head flexion/extension, be estimated by the (square root of) the sum of variances caused by reproduction of the reference position (SD: 1.4°) and the use of the inclinometer and software (SD: 1.3°, see above); that is, method SD: $1.9^\circ=(1.4^\circ\times 1.4^\circ+1.3^\circ\times 1.3^\circ)^{0.5}$. Since the reference position for the arms requires less participation from the subject, the imprecision for arm elevation is presumably smaller (see paragraph 4.4 below). The reproducibility of the reference positions may be improved by repeated recordings [34].

4.4. Between-days variability

Due to the hierarchic model, the imprecision of the method is included in the presented between-days variability. One illustrative example of this is the woman (subject B in Fig. 1) who, for one day, for all three percentiles and all three tasks, showed an almost constant deviation of her head flexion/extension, from the mean value. This offset is presumably caused by the imprecision in the recording of the reference position and is thus a component of the imprecision of the method, and does not reflect true behavioural between-days variability in her performance of the tasks. For the average individual, the true between-days variability may be estimated by compensating for the imprecision of the method. For example, the presented typical between-days variability of 3.0° for head flexion/extension, actually reflects a somewhat lower true between-days variability of $2.3^\circ=(3.0^\circ\times 3.0^\circ-1.9^\circ\times 1.9^\circ)^{0.5}$.

Neck flexion/extension is calculated as the difference between head and upper back flexion/extension. If the variability of the head and upper back are uncorrelated, the SD_{BD} for the neck (SD_{BD_neck}) would be related to the SD_{BD} for the head (SD_{BD_head}) and the upper back (SD_{BD_back}) according to: $SD_{BD\_neck}=(SD_{BD\_head}^2+SD_{BD\_back}^2)^{0.5}$. The present data supported this model. Hence, when neck angles are derived as the difference between head and upper back angles, SD_{BD} is expected to increase compared to its size for the individual segments, and, for equal segment SD_{BD}, at the most by a factor of $2^{0.5}$.

Regarding *upper arm elevation*, 'materials picking', showed the lowest SD_{BD}: for the 10th percentile, on average for the two sides, 1.8°. Hence, the precision of the method, as well as the reproducibility of the reference recordings for the upper arms, is better than this value. The slightly higher SD_{BD} for the higher percentiles indicates higher between-days variability for postures where the arms are elevated.

Very few previous studies have reported data on between-days variability for measurements of body postures during occupational work. Using a transducer that characterises the time spent in various sectors of inclination, variability in upper arm elevation above 90°, on average for 30 specified tasks, corresponding to SD_{BD} of 2.9% of the time, and a normalised SD_{BD} of 72% (at a mean value of 6.1% of the time) were found [31], which is in accordance with our results. As for the between-subjects variability (see below), this accordance regarding *variability* does not imply that there is an agreement regarding the *exposure values* obtained by the two methods during identical conditions.

Regarding *movements*, the variability in our data was small. The lower limit of CV_{BD} at 3% indicates, both that the variability caused by the method does not exceed 3% and that the individuals repeat their average movement pattern almost identically from day to day. Since movements are defined as changes in posture over time, they are, in contrast to postures, insensitive to errors in the determination of the reference positions.

4.5. Between-subjects variability

Regarding *postures*, the variability of the *percentile* values was, as for the between-days variability, in general low, indicating that the subjects adopted similar postures when performing the tasks. This is consistent with our observation that subjects did not differ obviously in the way they performed the tasks, and it is probably a result of the tasks being highly standardised, and the women differing only slightly in their anthropometrics. Thus, the present results may be considered as minimum values for standardised tasks.

Numerous studies of physical workload have reported the variability in exposure between subjects. In most of these studies, the subjects are measured for one day only, and in that case between-subjects variability is overestimated, since it also includes between-days, within-days and method variability [21]. For example, using the same measuring method as in the present study, gross between-subjects variability of, on average for three tasks, 8.6°, 4.6° and 8.0°, have been reported for the 50th percentiles of the head and right and left upper arm, respectively, for studying hand-held nutrunners in a mixed group of men and women, [22]. Considering the above remark, these values are consistent with the present results. Regarding time in angular sectors, using the present measuring method, Möller et al. [23] reported gross between-subjects variability, for head flexion and upper arm elevation >30°, which, on average, correspond to SD_{BS} of 26% time, and normalised SD_{BS} of 77%. As in the present study the normalised SD_{BS} is high, and considerably higher than CV_{BS} for the angular velocity percentiles.

Using a transducer that monitors the time spent in various sectors of inclination, Svendsen et al. [31] found a variability in upper arm elevation above 90° corresponding to SD_{BS} of

3.5%, at a mean value of 6.1% of the time across 30 specified tasks. Thus, their normalised SD_{BS} of 57% is almost identical to our results.

Data on *movements* reporting peak trunk angular velocity during standardised lifting tasks, recorded by an opto-electrical method, show CV_{BS} of 12% - 21% [18]. These values are almost identical to the corresponding ones in the present study (90th percentile for upper back flexion/extension angular velocity; 11% - 20%). Velocity variability was considerably larger between-subjects than between days within subject, which suggests that the movement pattern is a personal trait. For example, subject ‘F’ in Fig 2 displayed, for no obvious reason, higher angular velocities, especially for ‘materials picking’, than the other subjects. Since high velocity is a risk factor for developing WMSDs, this personal trait might be of significance, if it is considerable in relation to the effect imposed by the various tasks.

4.6. Applications

In epidemiologic studies using exposure-response regression, the validity and precision of the relations depends on the sizes of between- and within-subject exposure variability [32]. The presented between-days and between-subjects variability may be used as minimum estimates of these parameters in occupational settings, and as a basis for evaluating group-based and individual-based exposure assessment strategies. Specifically, when a group-bases strategy is applied, a high homogeneity of the exposed groups, i.e. a low variability between the subjects (including the within-subject variability), is essential, and the presented results constitute a reference for evaluating to what extent this criterion has been met.

In studies including different mono-task jobs, the root mean square value ($RMS=(\sum_{i=1}^{n}(x_i-x_m)^2/(n))^{0.5}$; $x_m=\sum_{i=1}^{n}(x_i)/n$; x_i= exposure value for task number i; n= number of tasks) of the exposure values for the different tasks, is an estimate of the contrast between-tasks, closely related to the variability (SD=$(\sum_{i=1}^{n}(x_i-x_m)^2/(n-1))^{0.5}$; annotations as above). For example, for the three tasks in the present material, the between-task RMS-values are 7.6° and 9.2°, for the 50th percentile of head flexion and right upper arm elevation, respectively. Although the three tasks all represent manual materials handling, these values are considerably higher than the corresponding between-days and between-subjects variability. A larger variability due to task than to subject or day is in accordance with other studies [3]. Moreover, many epidemiological studies include referents with contrasting exposures. This will further increase between-groups variability, and reduce the influence of between- and within-subjects exposure variability on the validity and precision of exposure-response relations.

Acknowledgements

This study was supported by the Swedish Medical Research Council, the Swedish Council for Work Life and Social Research, the Swedish Council for Work Life Research (including Change@Work), the Swedish National Institute of Working Life, the Swedish Council for Planning and Coordination of Research, AFA Insurance, the Medical Faculty of Lund University and the County Councils of Southern Sweden. Ms Lothy Granqvist and Ms Jeannette Unge, MSc, gave skilful technical assistance. Svend Erik Mathiassen did part of his work while being a visiting scholar with the Liberty Mutual Research Institute for Safety in Hopkinton, MA, USA.

References

[1] Aarås A, Westgaard RH, Stranden E. Postural angles as an indicator of postural load and muscular injury in occupational work situations. Ergonomics 1988;31:915-33.

[2] Åkesson I, Hansson G-Å, Balogh I, Moritz U, Skerfving S. Quantifying work load in neck, shoulders and wrists in female dentists. Int Arch Occup Environ Health 1997;69:461-74.

[3] Allread WG, Marras WS, Burr DL. Measuring trunk motions in industry: variation due to task factors, individual differences, and the amount of data collected. Ergonomics 2000;43:691-701.

[4] Balogh I, Hansson G-Å, Ohlsson K, Strömberg U, Skerfving S. Interindividual variation of physical load in a work task. Scand J Work Environ Health 1999;25:57-66.

[5] Balogh I, Ohlsson K, Hansson G-Å, Engström T, Skerfving S. Increasing the degree of automation in a production system – consequences for the physical workload. Int J Ind Ergon (in press).

[6] Bernard BP. Musculoskeletal disorders and workplace factors. A critical review of epidemiological evidence for work-related musculoskeletal disorders of the neck, upper extremity and low back. Cincinnati, OH, US: National Institute of Occupational Safety and Health, 1997.

[7] Bernmark E, Wiktorin C. A triaxial accelerometer for measuring arm movements. Appl Ergon 2002;33:541-7.

[8] Burdorf A, Verburgh A, Elders L. Time-dependent variation in back load of workers in a dairy factory. Ann Occup Hyg 1994;1:199-206.

[9] Buringh E, Lanting R. Exposure variability in the workplace: its implications for the assessment of compliance. Am Ind Hyg Assoc J 1991;52:6-13.

[10] Fallentin N. Regulatory actions to prevent work-related musculoskeletal disorders – the use of research-based exposure limits. Scand J Work Environ Health 2003;29:247-50.

[11] Fallentin N, Viikari-Juntura E, Wærsted M, Kilbom Å. Evaluation of physical workload standards and guidelines from a Nordic perspective. Scand J Work Environ Health 2001;27(Suppl 2):1-52.

[12] Hansson G-Å, Asterland P, Holmer N-G, Skerfving S. Validity and reliability of triaxial accelerometers for inclinometry in posture analysis. Med Biol Eng Comput 2001;39:405-13.

[13] Hansson G-Å, Asterland P, Kellerman M. Modular data logger system for physical workload measurements. Ergonomics 2003;46:407-15.

[14] Hansson G-Å, Balogh I, Unge Byström J, Ohlsson K, Nordander C, Asterland P, Sjölander S, Rylander L, Winkel J, Skerfving S. Questionnaire versus direct technical measurements in assessing postures and movements of the head, upper back, arms and hands. Scand J Work Environ Health 2001;27:30-40.

[15] ISO. Ergonomics - Evaluation of static working postures. 2000; ISO 11226.

[16] Juul-Kristensen B, Fallentin N, Ekdahl C. Criteria for classification of posture in repetitive work by observation methods: A review. Int J Ind Ergon 1997;19:397-411.

[17] Juul-Kristensen B, Hansson G-Å, Fallentin N, Andersen JH, Ekdahl C. Assessment of work postures and movements using a videobased observation method and direct technical measurements. Appl Ergon 2001;32:517-24.

[18] Kjellberg K, Lindbeck L, Hagberg M. Method and performance: two elements of work technique. Ergonomics 1998;41:798-816.

[19] Loomis D, Kromhout H. Exposure variability: concepts and applications in occupational epidemiology. Am J Ind Med 2004;45:113-22.

[20] Lyles RH, Kupper LL. On strategies for comparing occupational exposure data to limits. Am Ind Hyg Assoc J 1996;57:6-15.

[21] Mathiassen SE, Burdorf A, Van der Beek AJ. Statistical power and measurement allocation in ergonomic intervention studies assessing upper trapezius EMG amplitude – a case study of assembly work. J Electromyogr Kinesiol 2002;12:45-57.

[22] Mathiassen SE, Möller T, Forsman M. Variation in mechanical exposure within and between individuals performing a highly constrained industrial work task. Ergonomics 2003;46:800-24.

[23] Möller T, Mathiassen SE, Franzon H, Kihlberg S. Job enlargement and mechanical exposure variability in cyclic assembly work. Ergonomics 2004;47:19-40.

[24] National Research Council and the Institute of Medicine. Musculoskeletal disorders in the workplace: Low back and upper extremities. Panel on Musculoskeletal Disorders in the Workplace. Commission on Behavioral and Social Sciences and Education. Washington, DC: National Academy Press, 2001.

[25] Nordander C, Balogh I, Mathiassen SE, Ohlsson K, Unge J, Skerfving S, Hansson G-Å. Precision of measurements of physical workload during standardised manual handling Part I: Surface electromyography of *m. trapezius*, *m. infraspinatus* and the forearm extensors. J Electromyogr Kinesiol 2004;14:443-54.

[26] Rappaport SM, Lyles RH, Kupper LL. An exposure-assessment strategy accounting for within- and between-worker sources of variability. Ann Occup Hyg 1995;39:469-95.

[27] Sluiter JK, Rest KM, Frings-Dresen MH. Criteria document for evaluating the work-relatedness of upper-extremity musculoskeletal disorders. Scand J Work Environ Health 2001;27(Suppl 1):1-102.

[28] Solow B, Tallgren A. Natural head position in standing subjects. Acta Odont Scand 1971;29:591-607.

[29] Spielholz P, Silverstein B, Morgan M, Checkoway H, Kaufman J. Comparison of self-report, video observation and direct measurement methods for upper extremity musculoskeletal disorder physical risk factors. Ergonomics 2001;44:588-613.

[30] Svendsen SW, Bonde JP, Mathiassen SE, Stengaard-Pedersen K, Frich LH. Work-related shoulder disorders: quantitative exposure-response relationships with reference to arm posture. Occup Environ Med 2004;61:844-53.

[31] Svendsen SW, Mathiassen SE, Bonde JP. Task-based exposure assessment in ergonomic epidemiology: a study of upper arm elevation in the jobs of machinists, car mechanics, and house painters. Occup Environ Med 2005;62:18-26.

[32] Tielemans E, Kupper LL, Kromhout H, Heederik D, Houba R. Individual-based and group-based occupational exposure assessment: some equations to evaluate different strategies. Ann Occup Hyg 1998;42:115-9.

[33] Unge Byström J, Hansson G-Å, Rylander L, Ohlsson K, Källrot G, Skerfving S. Physical workload on neck and upper limb using two CAD applications. Appl Ergon 2002;33:63-74.

[34] Üşümez S, Orhan M. Inclinometer method for recording and transferring natural head position in cephalometrics. Am J Orthod Dentofacial Orthop 2001;120:664-70.

[35] Üşümez S, Orhan M. Reproducibility of natural head position measured with an inclinometer. Am J Orthod Dentofacial Orthop 2003;123:451-4.

[36] Van der Beek AJ, Frings-Dresen MHW. Assessment of mechanical exposure in ergonomic epidemiology. Occup Environ Med 1998;55:291-9.

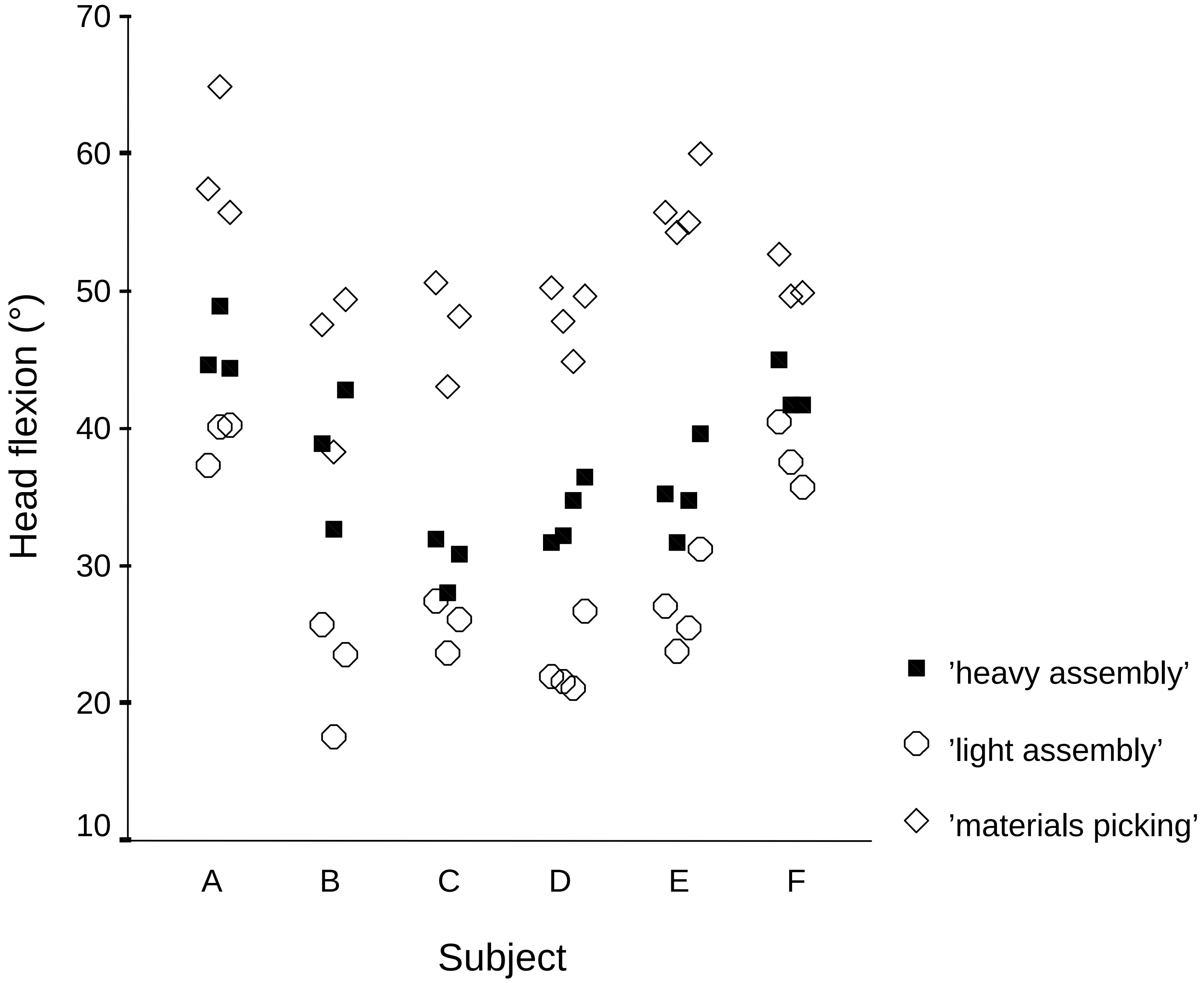
[37] Winkel J, Mathiassen SE. Assessment of physical work load in epidemiologic studies: concepts, issues and operational considerations. Ergonomics 1994;37:979-88.

Legends to the figures

Fig. 1. Head flexion/extension (90th percentile of the amplitude distribution), for six women (A-F), repeating the same three work tasks (‘materials picking’, ‘light assembly’ and ‘heavy assembly’) on three (for two of the women four) days. Each vertically aligned triplet represents the three tasks performed on one day.

Fig. 2. Left upper arm angular velocity (90th percentile of the generalised angular velocity distribution), for six women (A-F), repeating the same three work tasks (‘materials picking’, ‘light assembly’ and ‘heavy assembly’) on three (for two of the women four) days. Each vertically aligned triplet represents the three tasks performed on one day.

Fig. 3. Between-days (x) and between-subjects (o) exposure variability as a function of the mean value of % time spent in the 48 selected angular sectors, for the five studied body segments, and the three tasks: (a) variability in terms of SD; (b) variability expressed as SD/(min(mean, (100-mean))).


70
60
50
40
30
20
10
Head flexion (°)
A
B
C
D
E
F
Subject
'heavy assembly'
'light assembly'
'materials picking'

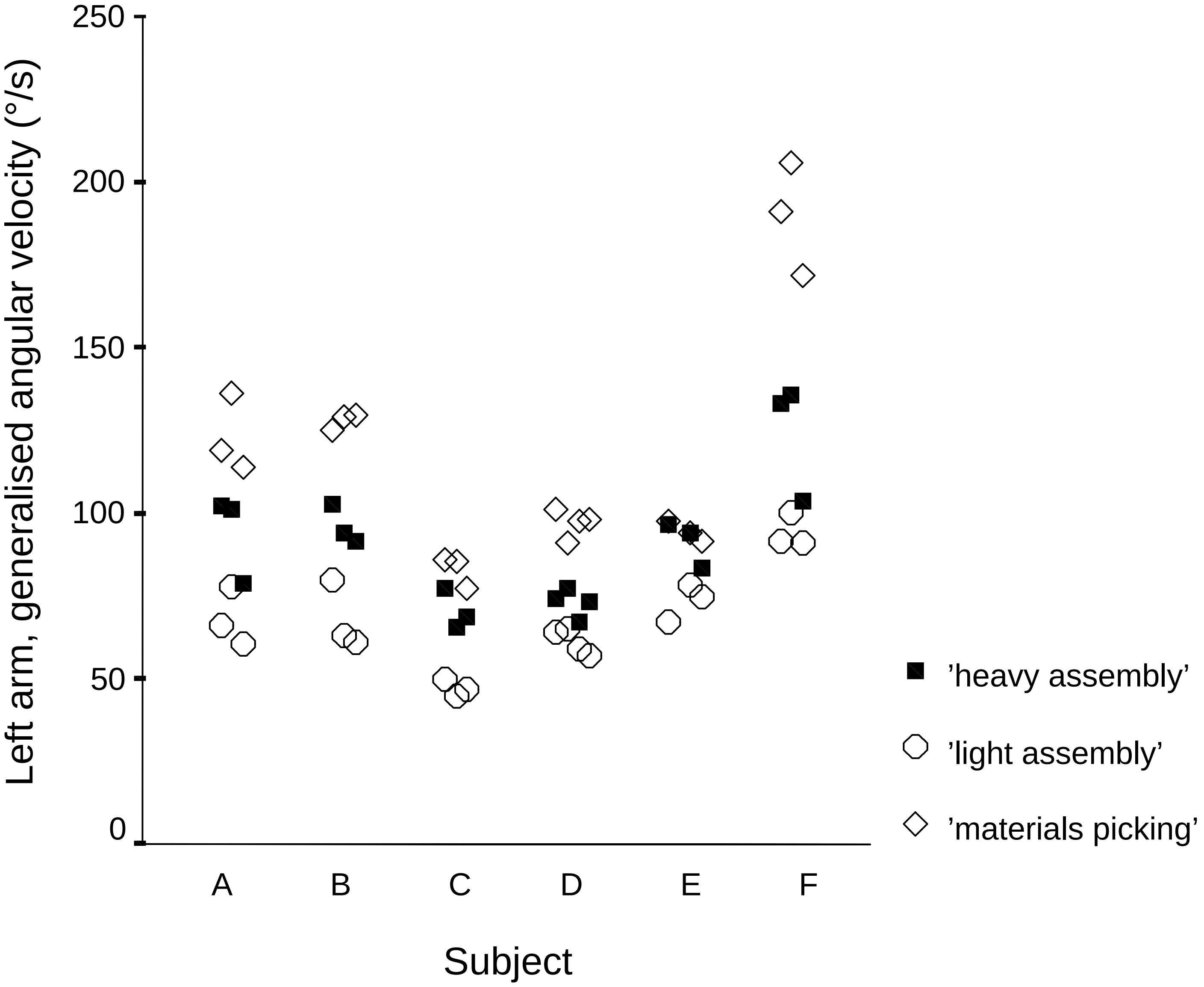

Left arm, generalised angular velocity (°/s)
250
200
150
100
50
0
A
B
C
D
E
F
Subject
'heavy assembly'
'light assembly'
'materials picking'

Table 1
Exposure variability of *posture percentiles* in terms of standard deviation (SD) between days (within subjects) and between subjects, as well as the mean value, for six women repeating the same three work tasks (‘materials picking’, ‘light assembly’ and ‘heavy assembly’) on three [a] different days. Data are shown for the 10th, 50th and 90th percentiles of the angular distributions. For the head, upper back and neck, positive values denote forward flexion/extension and lateral flexion to the right

Body segment	Distribution (percentile)	Task								
		‘Materials picking’			‘Light assembly’			‘Heavy assembly’		
		SD between			SD between			SD between		
		Days (°)	Subjects (°)	Mean (°)	Days (°)	Subjects (°)	Mean (°)	Days (°)	Subjects (°)	Mean (°)
Head										
Flexion/extension	10th	3.5	4.1	24	2.7	4.7	14	3.2	0.0	13
	50th	3.3	4.2	41	2.6	5.6	23	3.0	4.0	28
	90th	3.7	5.2	51	2.8	7.4	29	3.0	5.6	38
Lateral flexion	10th	1.6	1.3	-10	2.3	2.8	-9	2.4	3.1	-11
	50th	1.8	1.8	-1	1.9	3.3	-2	2.1	2.6	-4
	90th	1.8	2.2	10	2.0	2.7	6	2.1	2.5	3
Upper back										
Flexion/extension	10th	2.9	6.6	12	3.6	6.9	5	3.4	2.2	3
	50th	3.3	8.6	22	3.7	7.2	9	3.6	2.2	9
	90th	2.6	6.0	37	4.4	5.8	14	3.9	1.9	14
Lateral flexion	10th	3.8	3.5	-9	3.1	2.3	-6	2.7	2.8	-11
	50th	2.9	2.9	0	2.8	2.2	-3	2.4	2.7	-6
	90th	3.5	1.9	11	2.7	2.1	1	2.8	3.0	1
Neck										
Flexion/extension	10th	4.2	3.6	-1	5.2	5.4	3	4.7	1.3	3
	50th	3.3	5.2	17	4.9	5.6	14	4.5	3.4	20
	90th	3.8	4.9	30	5.0	5.6	21	4.5	4.6	31
Lateral flexion	10th	4.0	2.2	-12	2.8	3.6	-6	3.6	5.9	-7
	50th	3.4	3.3	-1	2.8	3.1	0	3.1	4.0	1
	90th	3.5	3.3	9	3.1	2.8	8	3.2	4.0	9
Upper arm elevation										
Right	10th	1.7	1.9	12	4.2	5.3	26	4.3	4.3	29
	50th	2.3	4.4	22	4.6	6.1	32	3.8	7.0	45
	90th	3.0	6.5	38	4.2	4.9	54	3.5	6.1	67
Left	10th	1.9	3.4	9	6.9	3.6	26	3.6	3.7	23
	50th	2.1	3.8	19	5.9	5.2	32	4.1	3.9	33
	90th	2.5	2.9	37	6.1	5.1	45	4.5	3.7	48

[a] Two women performed the tasks on four days. Missing data due to technical problems: one woman, right arm, all tasks on one day; one woman, left arm, task ‘materials picking’ on one day.

Table 2

Exposure variability of *posture categories* in terms of standard deviation (SD) between days (within subjects) and between subjects, as well as the mean value, for six women repeating the same three work tasks (‘materials picking’, ‘light assembly’ and ‘heavy assembly’) on three [a] different days. Data are shown for the fraction of the work time (%) spent in various posture categories. For the head, upper back and neck, positive values denote forward flexion/extension and lateral flexion to the right

Body segment	Categories (angle limits; °)	Task								
		‘Materials picking’			‘Light assembly’			‘Heavy assembly’		
		SD between			SD between			SD between		
		Days (% time)	Subjects (% time)	Mean (% time)	Days (% time)	Subjects (% time)	Mean (% time)	Days (% time)	Subjects (% time)	Mean (% time)
Head										
Flexion/extension	<-15	0.02	0.00	0.01	0.19	0.06	0.05	0.09	0.06	0.07
	>15	2.0	2.2	96	12	13	81	5.1	1.7	86
	>45	10	16	33	0.37	0.22	0.21	2.8	4.8	3.7
Lateral flexion	<-15 *or* >15	1.3	2.8	7.4	3.5	1.0	2.6	6.1	5.1	5.8
Upper back										
Flexion/extension	<-15	0.02	0.00	0.01	0.00	0.00	0.00	0.01	0.01	0.01
	>15	11	26	73	25	29	29	18	0.00	15
	>45	1.9	2.7	3.6	0.00	0.00	0.00	0.05	0.00	0.01
Lateral flexion	<-15 *or* >15	4.9	2.0	9.7	1.6	0.71	0.84	5.0	4.8	6.9
Neck										
Flexion/extension	<-15	1.1	0.65	2.4	0.66	0.54	0.45	0.98	0.00	0.91
	>15	10	16	54	22	21	44	14	14	63
	>45	0.41	0.34	0.26	0.06	0.00	0.02	0.59	0.12	0.26
Lateral flexion	<-15 *or* >15	7.4	4.8	11	3.3	1.2	3.9	4.9	4.9	7.6
Upper arm elevation										
Right	>30	5.8	13	24	21	19	62	8.3	6.1	86
	>60	0.35	0.64	0.67	2.9	4.3	5.4	5.2	12	20
Left	>30	5.5	5.6	21	24	21	60	16	13	62
	>60	0.36	0.27	0.55	2.5	1.5	2.5	1.3	1.7	2.6

[a] Two women performed the tasks on four days. Missing data due to technical problems: one woman, right arm, all tasks on one day; one woman, left arm, task ‘materials picking’ on one day.

Table 3
Exposure variability of *movements* in terms of coefficient of variation (CV) between days (within subjects) and between subjects, as well as the mean value, for six women, repeating the same three work tasks (‘materials picking’, ‘light assembly’ and ‘heavy assembly’) on three[a] different days. Data are shown for the 10th, 50th and 90th percentiles of the absolute angular velocity distributions

Body segment	Distribution (percentile)	Task								
		‘Materials picking’			‘Light assembly’			‘Heavy assembly’		
		CV between			CV between			CV between		
		Days (%)	Subjects (%)	Mean (°/s)	Days (%)	Subjects (%)	Mean (°/s)	Days (%)	Subjects (%)	Mean (°/s)
Head										
Flexion/extension	10th	8	25	1.4	11	17	1.4	7	12	1.7
	50th	5	16	9.9	10	17	8.3	6	10	10
	90th	6	9	42	7	12	29	6	12	39
Lateral flexion	10th	7	21	2.2	9	20	2.2	3	18	2.1
	50th	4	14	15	9	22	13	3	17	12
	90th	5	14	64	8	22	49	6	19	49
Upper back										
Flexion/extension	10th	11	34	1.4	11	23	1.1	5	23	1.3
	50th	7	22	10	11	23	6.7	5	21	8.0
	90th	7	11	41	10	20	23	7	19	31
Lateral flexion	10th	4	38	1.7	10	25	1.0	8	22	1.3
	50th	3	28	12	10	27	6.4	7	22	8.4
	90th	4	15	47	10	27	22	6	17	33
Neck										
Flexion/extension	10th	11	40	1.4	15	17	1.6	9	21	1.6
	50th	9	30	9.8	13	18	9.7	8	20	9.9
	90th	7	16	44	9	15	35	6	19	42
Lateral flexion	10th	4	31	2.7	9	22	2.7	3	20	2.6
	50th	3	23	18	8	22	16	3	19	16
	90th	5	17	75	9	21	59	5	19	61
Upper arm										
Right	10th	13	20	9.9	10	30	9.0	8	17	8.0
	50th	6	18	43	11	34	38	9	20	35
	90th	7	19	124	14	36	122	8	24	121
Left	10th	13	64	7.9	10	25	5.5	11	31	5.9
	50th	9	40	36	8	24	21	12	23	27
	90th	7	32	121	9	22	69	11	20	92

[a] Two women performed the tasks on four days. Missing data due to technical problems: one woman, right arm, all tasks on one day; one woman, left arm, task ‘materials picking’ on one day.

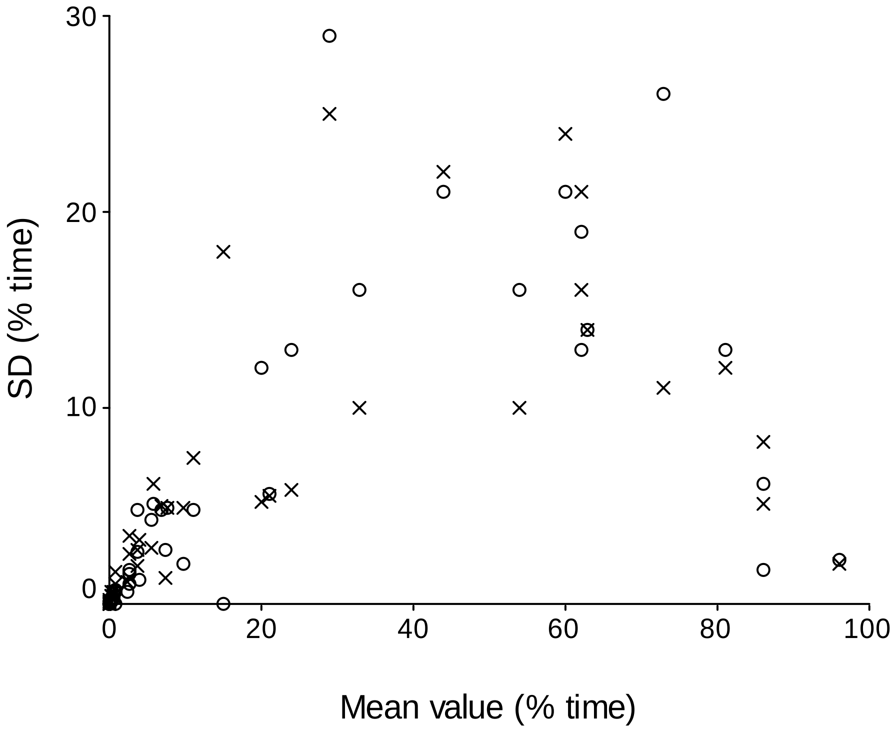


Fig. 3a. Hansson et al.: ”Precision of measurements ...”

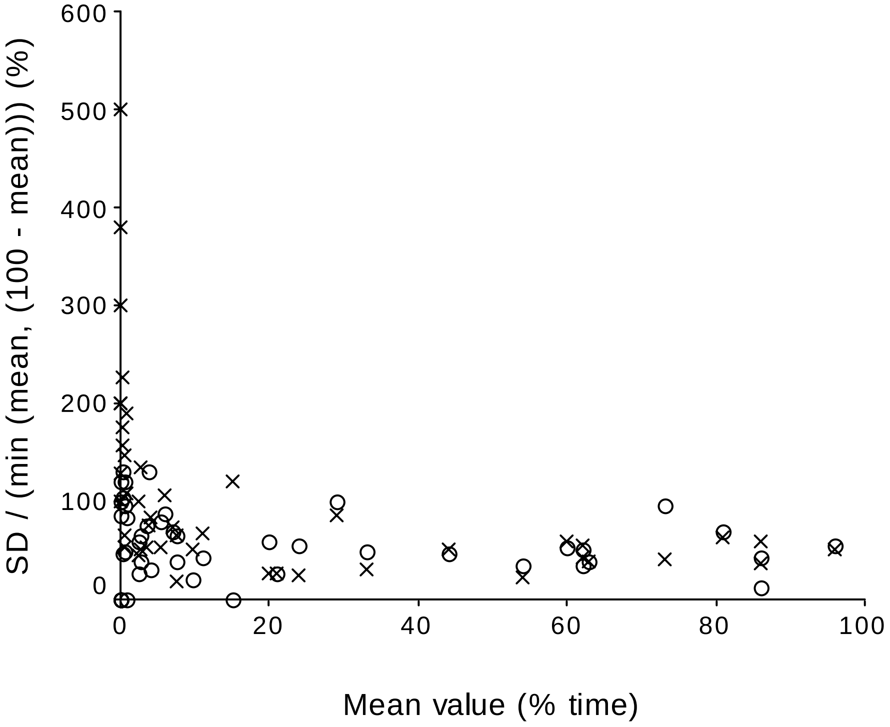


Fig. 3b. Hansson et al.: ”Precision of measurements ...”