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The ability of limited exposure sampling to detect effects of interventions that reduce the occurrence of pronounced trunk inclination

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A B S T R A C T

Ergonomics interventions often focus on reducing exposure in those parts of the job having the highest exposure levels, while leaving other parts unattended. A successful intervention will thus change the form of the job exposure distribution. This disqualifies standard methods for assessing the ability of various exposure measurement strategies to correctly detect an intervention's effect on the overall job exposure of an individual worker, in particular for the safety or ergonomics practitioner who with limited resources can only collect a few measurements. This study used a non-parametric simulation procedure to evaluate the relationship between the number of measurements collected during a self-paced manufacturing job undergoing ergonomics interventions of varying effectiveness, and the probability of correctly determining whether and to which extent the interventions reduced the overall occurrence of pronounced trunk inclination, defined as an inclination of at least 20°. Sixteen video-recordings taken at random times on multiple days for each of three workers were used to estimate the time distribution of each worker's exposure to pronounced trunk inclination. Nine hypothetical ergonomics intervention scenarios were simulated, in which the occurrence of pronounced trunk inclination in the upper 1/8, 1/4, and 1/2 of the job exposure distribution was reduced by 10%, 30% and 50%. Ten exposure measurement strategies were explored, collecting from one to ten pre- and post-intervention exposure samples from an individual worker. For each worker, intervention scenario and sampling strategy, data were bootstrapped from the measured (pre-intervention) and simulated (post-intervention) exposure distributions to generate empirical distributions of the estimated intervention effect. Results showed that for the one to three intervention scenarios that had the greatest effect on the overall occurrence of trunk inclination in the job, one to four pre- and post-intervention measurements, depending on worker, were sufficient to reach an 80% probability of detecting that the intervention did, indeed, have an effect. However, even for the intervention scenario that had the greatest effect on job exposure, seven or more samples were needed for two of the three workers to obtain a probability larger than 50% of estimating the magnitude of the intervention effect to within ±50% of its true size. For almost all interventions affecting 1/8 or 1/4 of the job, limited exposure sampling led to low probabilities of detecting any intervention effect, let alone its correct size.

1. Introduction

Extensive research has been performed to evaluate workplace interventions designed to reduce employee risks of contracting work-related musculoskeletal disorders (WMSD). This research includes numerous field and laboratory studies that have evaluated the effects of changes in tools, work methods, work environment or work organization. A number of recent reviews discuss different aspects of this large body of literature (e.g. Westgaard and Winkel, 1997; Silverstein and Clark, 2004; van der Molen et al., 2005; Brewer et al., 2006; Boocock et al., 2007; Denis et al., 2008). While the ultimate goal of the intervention is to reduce the risk of contracting or maintaining WMSD, changes in biomechanical exposure accompanying the intervention are often used as a proxy for its eventual effect on health (Westgaard and Winkel, 1997; Lötters and Burdorf, 2002; Cole et al., 2003). Due to constraints on time and resources, safety and ergonomics practitioners are particularly compelled to judging intervention effects by how they affect exposure.

There are significant challenges to quantifying the exposure effects of ergonomics interventions (Burdorf and van Riel, 1996;

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Burdorf and van Tongeren, 2003; Dempsey, 2007). One important issue appears from the growing literature demonstrating that biomechanical exposures often vary considerably across people within the same job or task, and over time for the same individual. Thus, postures and muscle activity of the back or upper extremities have been shown to vary between and within individuals in several settings, including dairy factory work, cyclic assembly work, cleaning and construction (Burdorf, 1993; Burdorf et al., 1994; van der Beek et al., 1995; Burdorf and van Riel, 1996; Paquet et al., 1999; van der Beek et al., 1999; Hoozemans et al., 2001; Mathiassen et al., 2002; van Dieën et al., 2002; Mathiassen et al., 2003a; Mathiassen et al., 2003b; Möller et al., 2004; Nordander et al., 2004; Paquet et al., 2005; Hansson et al., 2006; Jackson et al., 2009). This inherent exposure variability leads to uncertainties when limited samples of subjects and/or exposure data within a subject are collected and compared as a means of deciding whether an intervention is effective or not. With an insufficient sample size, the investigation will have a low ability to detect a true intervention effect; i.e. it lacks statistical power. The issue of determining a suitable measurement strategy is a challenge, both to researchers operating at the level of groups of workers with the aim of generalizing their results to other workers or other similar work situations, and to practitioners, who are often more interested in knowing whether or not specific individuals benefit from, for instance, modifications of their work station or a course in work technique.

Analytical methods are available by which the ability of an exposure assessment strategy to detect changes in the exposure mean can be estimated on the basis of data on exposure variability and allocated resources (Mathiassen et al., 2002; Mathiassen et al., 2003b). These methods are generally applicable for situations in which the compared pre- and post-intervention exposure distributions are both normal. Normality is a reasonable assumption if the compared mean exposures are both based on a large number of samples, since the distribution of a large-sample mean will approach normal, irrespective of the underlying distribution of the individual samples (Cochran, 1977). However, both in research (Mathiassen et al., 2002) and, in particular, in ergonomics practice (Paquet et al., 2006), exposure samples are often both few and short. While rarely addressed in intervention studies, pre- and post-intervention mean values cannot in this case be expected to be normally distributed without further study.

In ergonomics practice, improvements aimed at reducing the overall mean exposure are often focused on those parts of the job that are considered the worst or those that can be most easily improved upon, while the rest of the job is left unattended. A successful intervention will then change only parts of the overall exposure distribution. For an example, an intervention that reduces the upper 1/4 of a worker's exposures by 50% will, indeed, change the overall mean exposure, but it will also have a pronounced effect on the shape of the exposure distribution (Fig. 1). Thus, with interventions focusing only on the "worst" exposures, pre- and post-intervention exposures are unlikely both to be normally distributed. For instance, the occurrence of trunk flexion of at least 20° illustrated in Fig. 1 is normally distributed across the job before the "intervention", while afterwards it is not. Examples of intervention concepts with a scope of reducing large exposures while leaving lower ones unattended are courses in lifting technique intended to reduce biomechanical peak loads on the back (Martimo et al., 2008), and biofeedback devices returning an auditory or visual signal when a certain exposure level is exceeded (Madeleine et al., 2006; the Virtual Corset™ (www.microstrain.com/virtual-corset.aspx)).

In this practitioner's case of a successful intervention changing only a part of the exposure distribution, and the intervention effect being assessed on the basis of few pre- and post-intervention exposure samples from one or a few workers, standard analytical procedures cannot be used to evaluate the performance of exposure assessment strategies. Non-parametric approaches then offer a viable alternative. Statistical re-sampling techniques that do not rely on assumptions about the shape of the exposure distribution have been used previously to empirically test the performance of different measurement strategies for quantitative assessment of biomechanical exposures in the field (e.g., Burdorf and van Riel, 1996; Hoozemans et al., 2001; Mathiassen et al., 2002; Mathiassen et al., 2005; Paquet et al., 2005; Fethke et al., 2007), but these methods have not previously been used to investigate ergonomics intervention assessment practices.

The objective of this empirical simulation study was to evaluate the relationship between the number of measurements collected before and after ergonomics interventions of varying effectiveness in a self-paced manufacturing job, and the probability of correctly determining whether and to which extent the interventions reduced the overall occurrence of pronounced trunk inclination, defined as inclination of at least 20°. Taking a practitioner's rather than researcher's perspective, the study was designed to evaluate this relationship for interventions carried out on individual workers, and assessed by few measurements.

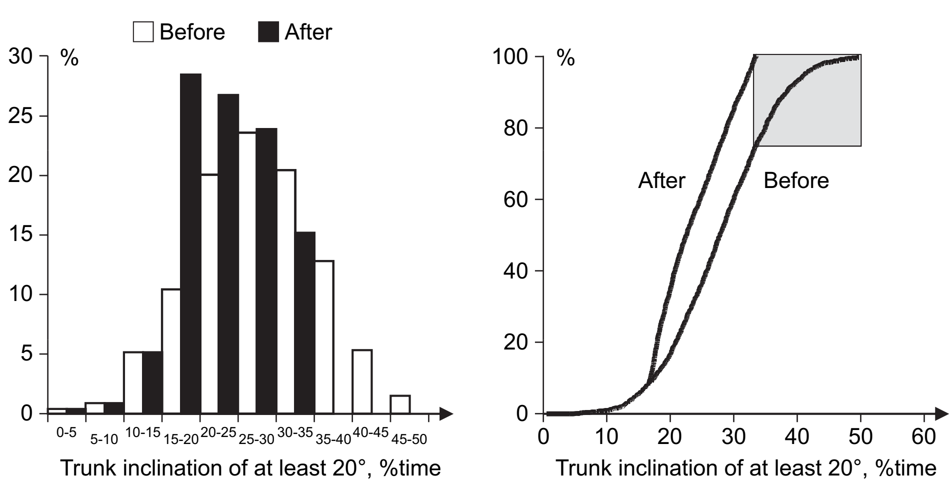

Fig. 1. Frequency distribution (left panel) and cumulative distribution (right panel) of the percent of time an individual spends in trunk inclination of at least 20° before and after an intervention that reduce the upper 1/4 of the exposure distribution (shaded) by 50%. The distributions are based on a very large number of hypothetical work samples, each one analyzed for the occurrence of trunk inclination.

2. Methods

2.1. Exposure data

Three workers performing the same physically demanding job were randomly selected from a convenience sample of nine workers at a manufacturing plant to provide realistic biomechanical exposure distributions at an individual level. The job was a self-paced automotive upsetting manufacturing job that required the following tasks: lift a steel rod weighing between 45 and 70 N from a pallet (depending on the batch), place rod in an electrical heater, place the rod into a die casting machine, operate the machine while adjusting the rod to achieve the desired shape, and store the newly formed part on a pallet. The pace of work was variable with cycle times ranging from 17 to 35 s. Workers had to frequently assume awkward body postures when loading, operating and unloading the die casting machine. The work height of the machine and heights of the pallets were fixed.

Each of the three workers was video recorded for at least ten work cycles on each of 16 occasions across five to six days during a period of several weeks. Measurement periods were stratified at three different times throughout the day (early, middle and late shift). Therefore data collection within a particular worker was not exactly balanced within and across days, but it did represent the variability of exposures both within and between days for that worker. The mean duration of a video recording was 2.95 min (SD 0.78 min), while the mean cycle time in the work captured on the videos was 18.5 s (SD 4.1 s).

The set of 16 video recordings was used to estimate the distributions of each worker's exposure to a variety of variables. For the present study, the percentage of time spent by the worker in "pronounced" trunk inclination, defined as an inclination of at least 20°, was selected. Reviews of the scientific literature have established a general association between low back pain and awkward trunk postures (e.g. Bernard, 1997; Burdorf and Sorock, 1997; Keyserling, 2000), and a reduction in trunk inclination has been used to demonstrate the effectiveness of ergonomics interventions aimed at reducing risk of low back disorders (e.g. Alders and Hudock, 2007). Researchers have even found associations between the specific trunk inclination parameter used in the present study and low back symptoms (e.g., Punnett et al., 1991), The European standard EN 1005-4 on working postures and movements in relation to machinery also identifies trunk inclination exceeding 20° as a potential risk factor (CEN, 2005). Many observational-based methods use this or a similar exposure metric to characterize awkward trunk postures at work (e.g., Karhu et al., 1977; Keyserling, 1986; Buchholz et al., 1996; Juul-Kristensen et al., 1997).

A computerized analysis package that allows systematic ergonomics assessment of video data (MVTA™, NexGen Ergonomics, Inc.) was used to evaluate each video recording. The video recording could be played in slow-motion or at full speed with the software. The presence of exposure to trunk inclination of at least 20°, relative to the line of gravity, was coded as a continuous event in time by an experienced observer. While not explicitly assessed in the present study, the within- and between-observer variability of this observation procedure can be assumed to be similar to that of corresponding methods used in ergonomics research and practice (Table 5 in Denis et al., 2000). On the basis of the observed event time line, the percentage of time spent in "pronounced" trunk inclination of at least 20°, was determined for each video recording and worker (Fig. 2). For convenience, the workers were numbered post-hoc in increasing order according to their overall occurrence of pronounced trunk inclination in the job.

The overall percentage time spent in trunk inclination of at least 20° in the job, as estimated by the mean value across the 16 video

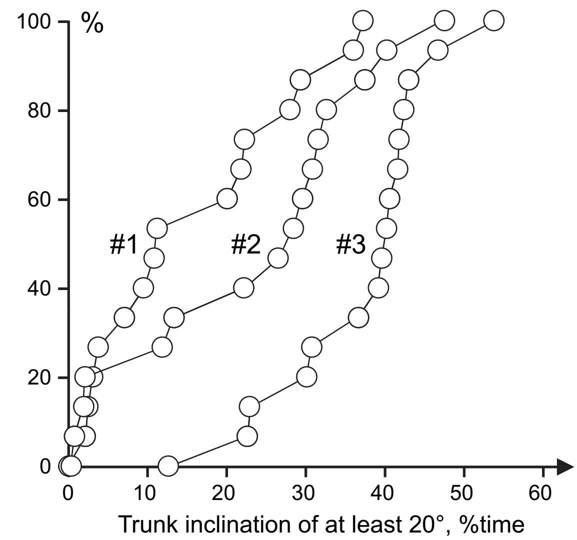

Fig. 2. Cumulative distribution of exposure to trunk inclination of at least 20° for each worker, as identified by numbers 1–3.

recordings, was 15.4 %time for worker #1 (SD 12.6 %time, range 0–37 %time), 22.2 %time for worker #2 (SD 15.3 %time, range 1–47 %time), and 36.2 %time for worker #3 (SD 10.3 %time, range 12–54 %time). One-way analysis of variance showed that the overall occurrence of pronounced trunk inclination differed significantly across workers ($F = 10.9$ with d.o.f = 2,45), and post-hoc Student's T-tests of samples with unequal variances demonstrated that worker #3 was more exposed than workers 1 and 2 ($p < 0.01$, $T = 5.2$ with d.o.f.=28 and $T = 3.0$ with d.o.f. = 28, respectively).

For the simulation, the exposure distribution of the 16 video recordings obtained for each worker (Fig. 2) was assumed to represent that worker's true long-term exposure distribution. Similarly, the studied intervention scenarios (below) were based on the assumption that the intervention affected the "true distribution" of a worker's exposure in the same way as it affected the distribution of this limited sample.

2.2. Simulated interventions

Interventions were simulated to affect those parts of the job for which the largest proportions of time were spent in pronounced trunk inclination. For each worker, nine hypothetical intervention scenarios were constructed, representing different impacts on exposure in terms of dissemination (intervention affecting those parts of the job responsible for the upper 1/8, 1/4, and 1/2 of the exposure distribution) and magnitude (in those parts of the job, the proportion of time spent in pronounced trunk inclination was reduced by 10%, 30% and 50%). In the studied self-paced automotive manufacturing work, feasible technical interventions having such an impact on the exposure distribution could include changes in the locations of the pallets, controls on the die casting machines or a complete redesign of the entire workstation. The interventions could also represent working technique courses that are successful to different extents.

The least effective intervention scenario, i.e. reducing exposure by 10% for the upper 1/8 of the job, represented a modest job exposure reduction: approximately a 0.5 %time reduction in the overall occurrence of trunk inclination of at least 20° for the 3 workers (Table 1). The intervention scenario having the greatest effect, i.e. reducing exposures by 50% for 1/2 of the job, represented between 6.5 %time and 10.9 %time reduction in job exposure across the workers. Thus, for worker 3 as an example, this intervention

Table 1
True effects of the nine simulated intervention scenarios for each worker. Numbers show the reduction in the overall time proportion of the job spent with a trunk inclination of at least 20°.

Intervention	Effect (%time)		
	Worker #1	Worker #2	Worker #3
Upper 1/2 of exposure distribution:			
- reduced by 50%	6.5	8.7	10.9
- reduced by 30%	3.9	5.2	6.6
- reduced by 10%	1.3	1.7	2.2
Upper 1/4 of exposure distribution:			
- reduced by 50%	4.1	4.9	5.8
- reduced by 30%	2.5	2.9	3.5
- reduced by 10%	0.8	1.0	1.2
Upper 1/8 of exposure distribution:			
- reduced by 50%	2.3	2.7	3.1
- reduced by 30%	1.4	1.6	1.9
- reduced by 10%	0.5	0.5	0.6

decreased the percentage time of the job spent with the trunk inclined at least 20° from 36.2 %time to 25.3 %time. Since the shape of the pre-intervention exposure distribution differed between workers, the intervention scenarios had differential effects, not only on the overall job exposure, but also on the shape of each worker's exposure distribution (Figs. 3–5).

2.3. Simulated exposure sampling strategies

Ten sampling strategies were investigated, with the number of randomly sampled pre- and post intervention measurement periods, i.e. video recordings, ranging from 1 to 10.

For each measurement strategy, the appropriate number of measurement periods was randomly selected with replacement from the parent pre- and post-intervention exposure distributions of each worker, using a bootstrap approach (Diaconis and Efron, 1983; Davison and Hinkley, 1997). For each worker, 2000 pre- and post-intervention sets of measurements were obtained for each of the 90 combinations of measurement strategy (n = 10) and intervention scenario (n = 9). For each set of measurements, pre- and post-intervention mean values were calculated as estimates of the overall occurrence of pronounced trunk inclination in the job, and their difference, i.e. the intervention effect, was determined. Thus, 2000 estimates of the size of this effect were available for each intervention scenario, sampling strategy and worker. In some cases, pre- and post-intervention samples were identical, leading to the estimated intervention effect being a genuine zero. This is an effect of the present bootstrap simulation approach *per se*, in being based on parent pre- and (simulated) post-intervention exposure distributions that were partly equal. Genuine zero effects would occur very rarely in occupational practice, even if pre- and post-intervention measurements were collected from identical parts of the job. In order to compensate for this simulation artifact, half of the genuine zeros were registered as showing a positive intervention effect and half were registered as negative. Examination of the data showed that the probability of getting identical pre- and post-intervention samples was below 0.01 for all sampling strategies employing two or more measurements.

2.4. Sampling performance parameters

On the basis of the 2000 effect size estimates for a particular combination of intervention and sampling strategy, two summary parameters were calculated to describe the performance of the sampling strategy under that intervention scenario: 1) the probability of correctly identifying that the intervention did, indeed, reduce job exposure, calculated as the proportion of the 2000 estimates showing a reduction, and, 2) the probability that the

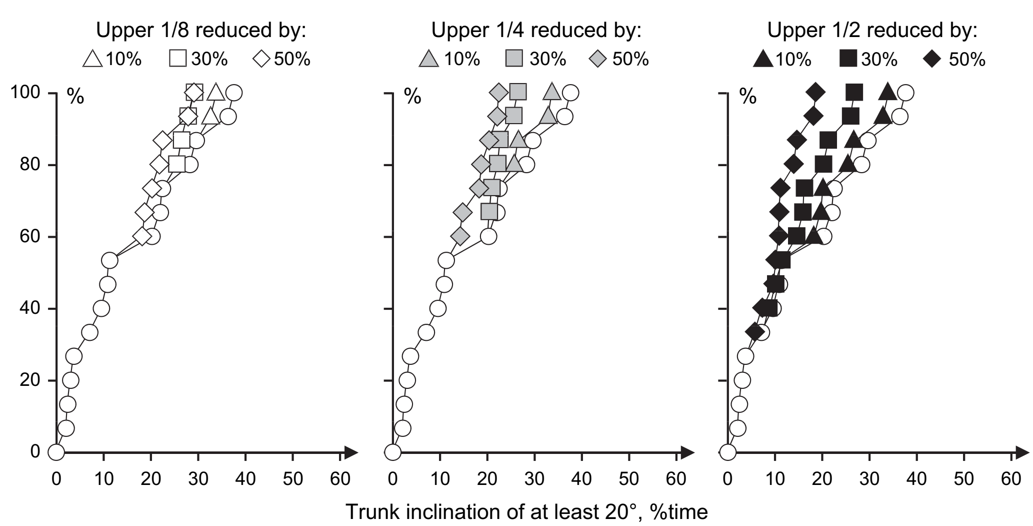

Fig. 3. Cumulative exposure distributions of worker #1 to trunk inclination of at least 20° for interventions that reduce the occurrence of trunk inclination in the upper 1/8, 1/4 and 1/2 of the distribution by 10%, 30% and 50%. Circles indicate pre-intervention distribution (cf. Fig. 2). For clarity, post-intervention distributions are only shown where they differ from pre-intervention.

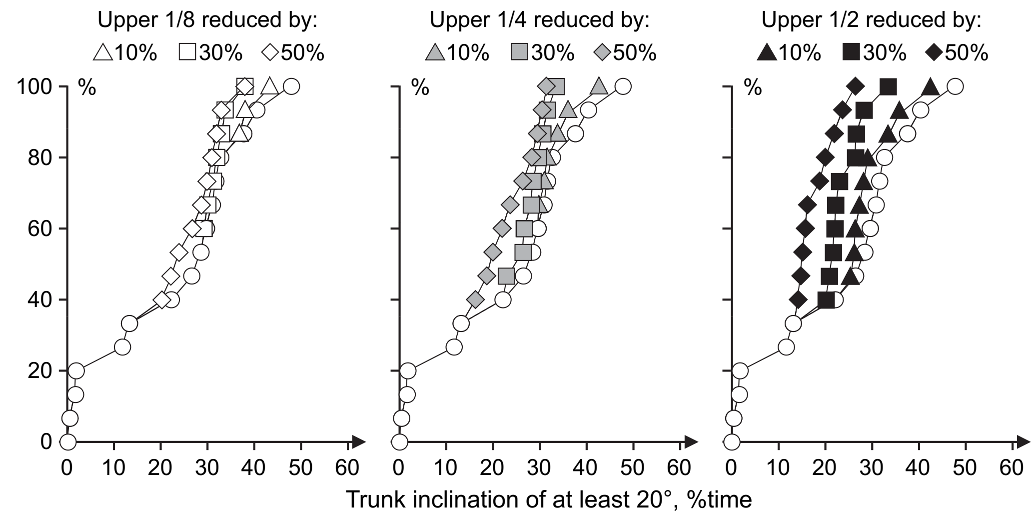

Fig. 4. Cumulative exposure distributions of worker #2 to trunk inclination of at least 20° for interventions that reduce the occurrence of trunk inclination in the upper 1/8, 1/4 and 1/2 of the distribution by 10%, 30% and 50%. Circles indicate pre-intervention distribution (cf. Fig. 2). For clarity, post-intervention distributions are only shown where they differ from pre-intervention.

reduction in exposure was measured to within ±50% of the correct reduction, calculated as the proportion of the 2000 estimates having a value within the interval [R-0.5R;R+0.5R], where R is the true reduction in job exposure (cf. Table 1). For the first criterion, a probability of 0.8 was considered an acceptable performance of the sampling strategy. A probability of only 0.5 was considered an acceptable performance on the second criterion because accurate quantification of the intervention effect was anticipated to be difficult. These criteria for "acceptability" were somewhat arbitrary but were set up as a basis by which the sampling strategies could be compared across the different intervention scenarios.

3. Results

3.1. Detecting a reduction in the overall job exposure

As expected, the ability of a sampling strategy to correctly detect that the intervention reduced the overall occurrence of pronounced trunk inclination generally increased with an increasing number of pre- and post-intervention measurements (Fig. 6). For all three workers, this ability was acceptable ($p > 0.8$) for sampling strategies with three or more pre- and post-intervention measurements when the most extreme half of the exposure distribution was reduced by 50%. The probability of detecting a reduction in job exposure remained below 0.8 for workers 1 and 2 for all other intervention scenarios if less than nine measurement periods were sampled. The detection probability was not much greater than chance (i.e., $p = 0.5$) for any sampling strategy when the intervention reduced either the upper one-quarter or upper one-eighth of the exposure distribution by 10%.

Large differences were observed across workers in the ability of a particular sampling strategy to detect an intervention effect. As an example, for worker #3, as few as five pre- and post-measurements were sufficient to achieve an acceptable ability to detect the job exposure reduction in the intervention decreasing exposure in 1/4 of the job by 50%. For worker #1, nine measurements were needed in this condition, and for worker #2 more than ten.

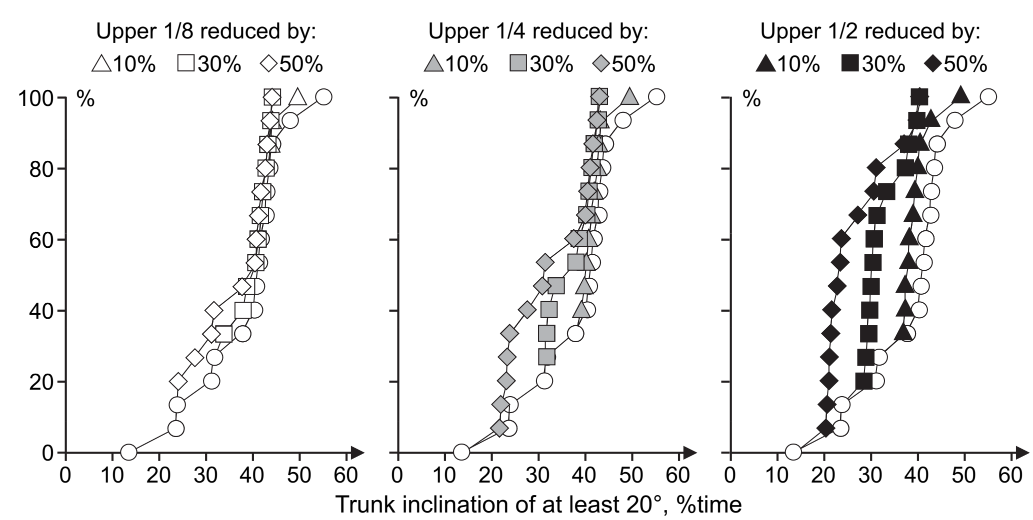

Fig. 5. Cumulative exposure distributions of worker #3 to trunk inclination of at least 20° for interventions that reduce the occurrence of trunk inclination in the upper 1/8, 1/4 and 1/2 of the distribution by 10%, 30% and 50%. Circles indicate pre-intervention distribution (cf. Fig. 2). For clarity, post-intervention distributions are only shown where they differ from pre-intervention.

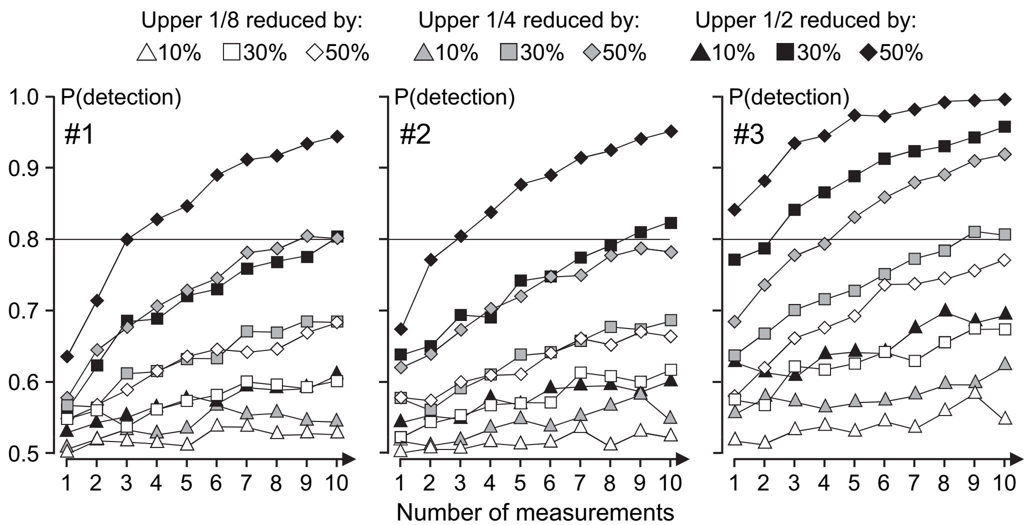

Fig. 6. Probability of detecting any reduction in the overall occurrence of trunk inclination in the job for each worker (#1, #2, #3), for each of the nine simulated intervention scenarios and with sampling approaches ranging from one to ten pre- and post-intervention measurements. Horizontal lines show suggested acceptance limit (see text).

3.2. Determining the reduction in job exposure to within 50% of its true size

The ability of the sampling strategy to identify the magnitude of the intervention effect to within 50% of its true size increased with larger number of samples but the performance was not promising for most cases (Fig. 7). For workers #1 and #2, the probability of getting a close-to-exact effect estimate exceeded 0.5 only for the intervention scenario in which the upper 1/2 of the exposure distribution was reduced by 50%, and only if at least seven pre- and post-intervention measurements were made. Only three pre- and post-intervention measurements were necessary to reach the same performance for worker #3. For this same worker, six pre- and post-intervention measurements were sufficient when the upper half of the exposure distribution was reduced by 30%. The probability of determining the intervention effect to within 50% of its true size was below 0.5 for almost all of the other sampling strategies, irrespective of worker.

4. Discussion

4.1. Job exposure assessment for interventions

While ergonomics interventions are usually aimed to reduce the risk of MSD, intervention effects on biomechanical exposure are often used as proxies of health effects, assuming that exposure is predictive of risk (Westgaard and Winkel, 1997; Lötters and Burdorf, 2002; Cole et al., 2003). One major reason is that the exposure effects of an intervention have a much shorter latency (if any) than health outcomes, making them more readily accessible, in particular to practitioners. Thus, a large body of literature has been devoted to methods for measuring intervention effects on trunk inclination at work (e.g., Marras et al., 1993; McAtamney and Corlett, 1993; Fransson-Hall et al., 1995; van der Beek et al., 1995; Buchholz et al., 1996; Hansson et al., 2001), supported by considerable epidemiologic evidence that trunk inclination is, indeed, a valid proxy of low back disorders (Punnett et al., 1991; Norman

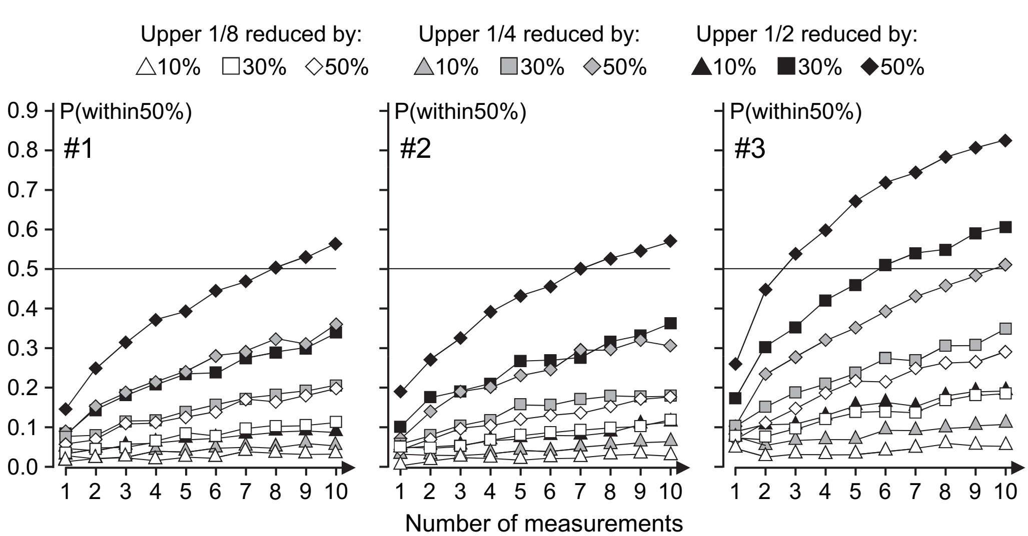

Fig. 7. Probability of estimating the reduction in the overall occurrence of trunk inclination in the job to within 50% of the true reduction (cf. Table 1) for each worker (#1, #2, #3), for each of the nine simulated intervention scenarios and with sampling approaches ranging from one to ten pre- and post-intervention measurements. Horizontal lines show suggested acceptance limit (see text).

et al., 1998; Vingård et al., 2000; Kerr et al., 2001; Hoogendoorn et al., 2002; van den Heuvel et al., 2004).

The need to develop measurement strategies that can, with a satisfactory reliability, detect intervention effects on ergonomics exposures such as trunk inclination has been emphasized by several researchers (e.g., Burdorf and van der Beek, 1999; Hagberg et al., 2001), and efficient sampling practices in terms of the number and allocation of exposure samples has been identified as a specific research issue of high priority (Burdorf and van der Beek, 1999; David, 2005; Burdorf, 2007; Wegman et al., 2007). While several methodological aspects of posture assessment by observation have been addressed in extensive reviews (Kilbom, 1994; Juul-Kristensen et al., 1997; Li and Buckle, 1999; Denis et al., 2000), sampling performance has received comparatively limited attention (Burdorf and van Riel, 1996; Hoozemans et al., 2001; Paquet et al., 2005). The challenges associated with documenting exposure effects of an intervention are, however, significant, particularly when quantitative estimates are desired (Dempsey, 2007). One reason is that the effects that an intervention has on an individual's exposure distribution are likely to be complex. For instance, Burdorf and colleagues found that mechanical tool interventions for construction work changed both the task distribution and the variability of workers' exposures to biomechanical exposures within and across tasks (Burdorf et al., 2007). This casts doubt on the common approach of evaluating the effects of interventions in an isolated task only by examining whether exposure changed in that particular task, as practiced for instance in investigations of the effect on trunk posture of modified tools (Marras et al., 2000), alternative equipment (Paskiewicz and Fathallah, 2007) or an adjusted work station (Straker and Mekhora, 2000).

While the effect of the intervention on the specific target task may be important information as to its ability of having any impact on exposure at all, it does not disclose the result of the intervention in the context of the whole job. In all of the mentioned task-oriented trunk posture interventions, a changed form and location of the resulting job exposure distribution is a probable result. As an example, the introduction of a new rebar-tying machine in construction work was documented by Vi (Vi, 2006) to dramatically change the upper parts of the trunk inclination distribution in the job while leaving the lower parts unaffected. In principle, the job-level effect may be estimated if the proportions of the changed task in the job before and after the intervention are known, and if exposure during the rest of the job is also known, or assumed to be unchanged. Considering, however, that an intervention may well change exposure levels as well as durations of tasks that were not the primary intervention targets (Burdorf et al., 2007), and considering that assessment of job exposure on the basis of exposures and proportions of all tasks in the job may not be efficient (Mathiassen et al., 2003a), sampling from the whole job may often be the preferable strategy, even in the case of alleged "isolated" interventions in routinized jobs (Gold et al., 2006).

The need for a job-level assessment is even more apparent in the case of interventions with a purpose of changing individual behavior across the entire job, such as the use of on-the-job biofeedback or courses in working technique. In this case, the intervention may affect only the most extreme exposures, and to different extents in different job tasks. Thus, the ergonomist would not know exactly when in time these behavioral events might take place. For such a situation, an ergonomics evaluation approach that focused only on one part of the job would not be viable; and a representative sample of exposure during the entire job is needed to characterize the effects of the intervention.

Standard analytical methods for assessing the performance of limited sampling on the basis of exposure variabilities within and between individuals (Mathiassen et al., 2002; Mathiassen et al., 2003a; Mathiassen et al., 2003b) require normally distributed data with homogeneous variances. The mentioned studies by Burdorf and colleagues (Burdorf et al., 2007) and Vi (Vi, 2006) illustrate situations where these assumptions were probably not met. The intervention investigated in the present study was deliberately constructed to represent a realistic violation of the normality assumption: an intervention changes the shape of the job exposure distribution, and only few exposure samples are collected as the basis for estimating the job exposure of an individual before and after the change. In this case, the practitioner faces the question of whether these exposure estimates will identify the true effect of the intervention, and thus lead to correct inferences as to whether or not the intervention was successful.

When violated assumptions disqualify analytical methods for examining the performance of measurement strategies, alternative approaches are needed, which are not equally dependent on those assumptions. In spite of this, and even though non-normal distributions within individuals are probably common for most occupational exposures, the extensive occupational hygiene literature dealing with measurement strategies for airborne or dermal exposures is remarkably committed to using only analytical tools, as illustrated by a recent textbook in the field (Rappaport and Kupper, 2008) as well as by key publications devoted to, e.g. compliance with limits (Rappaport et al., 1995), determinants of exposure (Burstyn and Teschke, 1999), exposure modeling (Preller et al., 1995), or exposure-outcome relationships (Tielemans et al., 1998).

4.2. Simulated interventions and sampling strategies

Bootstrapping, as used in the present and other papers on biomechanical exposure assessment strategies (e.g., Burdorf and van Riel, 1996; Hoozemans et al., 2001; Mathiassen et al., 2002; Mathiassen et al., 2005; Paquet et al., 2005; Fethke et al., 2007), offers a viable, simulation-based alternative to standard analytical methods in cases where the distributional form is problematic, since it is entirely based on the available empirical exposure distributions. The number of pre- and post intervention measurement periods used in the present simulations (one to ten) was intended to capture a range of what may often be used in practice or research. A survey conducted by Paquet and colleagues (Paquet et al., 2006) showed that a common video-based exposure assessment strategy among ergonomics practitioners in the US involves less than three workers, each one followed for less than five minutes. In research, ten or fewer work cycles have been used to characterize posture profiles in many studies of "repetitive" work, both for epidemiologic purposes (e.g., Harber et al., 1992; Marras et al., 1993; Ohlsson et al., 1995; Fallentin et al., 2001) and in ergonomics intervention evaluation (e.g., Häkkänen et al., 1997; Björing and Hägg, 2000). In less routinized jobs, posture recording periods of less than one hour are common, both in observation-based studies (Burdorf, 1992; Burdorf et al., 1997; Rolander et al., 2005; van der Beek et al., 2005), and when technical measurement equipment has been used (e.g., Bao et al., 1996; Vasseljen and Westgaard, 1997; Juul-Kristensen et al., 2001; Balogh et al., 2006).

The intervention scenarios selected for this study were intended to represent a set of feasible interventions of varying effectiveness, ranging from fairly modest – a 10% reduction in exposure for the upper 1/8 of the exposure distribution, causing the occurrence of pronounced trunk inclination in the job to decrease by about 0.5 %time, cf. Table 1 – to substantial: a 50% reduction in exposure for the upper 1/2 of the exposure distribution, leading to 6.5–10.9 percent of the job changing from being performed with a trunk inclination larger than 20° to being performed at less than 20°. These interventions were conducted in a job with an occurrence of trunk inclination in the same order of magnitude as in refuse collection (van der Beek et al., 1995), transportation (van der Beek et al., 1995) and furniture removing (Fransson-Hall et al., 1995), while being larger than in dairy work (Burdorf and van Riel, 1996) and nursing (van der Beek et al., 1995). The most effective intervention scenario resulted in an exposure change corresponding to the difference in occurrence of pronounced trunk inclination between refuse collectors and truck drivers reported by van der Beek and colleagues (van der Beek et al., 1995; the study addressed inclination of at least 15°). The core concept of the intervention scenarios was to reduce the overall occurrence of pronounced trunk inclination through a reduction in those parts of the job showing the highest exposure, rather than through a general shift of the entire exposure distribution. The intervention scenarios were constructed so that exposures were reduced as a percentage of the pre-intervention exposures. A proportional intervention effect is consistent with, for example, increasing the work heights or decreasing the reach distances so that all workers will receive some benefit, but with the greatest absolute reduction in exposure to the one who might for example have the largest stature or smallest reaching ability.

4.3. Sampling performance

One principal finding of the study was that a fairly large number of samples were required to reliably detect a change in job exposure for all but the most dramatic intervention scenarios, at least for two out of the three studied workers (cf. Fig. 6). For the least effective interventions, the probability of detecting an effect, even with ten exposure samples pre- and post-intervention, barely exceeded that obtained by guessing. Most sampling strategies failed to determine the correct size of any of the intervention effects to within reasonable limits (cf. Fig. 7). The study thus confirmed the trivial finding of more samples leading to a better performance, as documented in theoretical (Samuels et al., 1985) as well as empirical studies (Allread et al., 2000; Hoozemans et al., 2001; van Dieën et al., 2002). The small deviations from a regular expected effect of increased sampling seen for some interventions in some worker(s) can be explained by the performance estimates being somewhat uncertain due to the random properties of the bootstrapping procedure and the limited number of measurements (i.e. 16) used to define each worker's exposure distribution. Notably, our results did show that even sampling in excess of what is normally considered by practitioners may not be sufficient for their purposes.

Because each worker's pre-intervention exposure distribution differed, the intervention scenarios had differential effects on the exposure distributions across workers (Figs. 3–5). For the three workers included in this study, worker #3 had the highest overall proportion of trunk inclination in the job and an exposure distribution that was more dramatically skewed as compared to workers #1 and #2 (cf. Fig. 2). This fact, in combination with the intervention scenarios designed to imply proportional shifts of the upper portions of the exposure distribution, explains that the simulated interventions had the greatest effects on worker #3 (Fig. 5). This, in turn, is a major reason that sampling requirements to reliably identify the effects of the interventions were consistently less for worker #3 than for workers #1 and #2.

Due to the limited number of workers in this study, the data set did not permit further investigation into a possible relationship between the specific characteristics of the actual exposure distribution and the probability of successfully identifying a change in exposure or evaluating its size. Rather, the results illustrate that a practitioner facing the task of evaluating an intervention on a particular worker must be aware that the variability between individuals in pre-intervention exposure as well as in possible intervention effects (cf. Figs. 3–5) calls for a generous sample size to secure a sufficient sensitivity of the evaluation irrespective of what particular characteristics the target worker may have.

Also, our exposure data was too limited to permit an analysis of possible determinants of exposure within the individual. Candidates for systematic causes of exposure variability could be time of day or day of week. If a systematic effect existed for these or other determinants, stratified exposure assessment strategies could be developed, which might lead to a better performance for a given number of samples, or, equivalently, give a desired performance with less investment of resources (Cochran, 1977). While the present video recordings were, indeed, stratified so as to represent different times during the working day, we do not have sufficient information to conclude whether this did or did not improve efficiency as compared to random sampling. Thus, we cannot at present recommend any particular structure of sampling across time beyond what has previously been published by others, including the general recommendation to distribute samples across multiple days if possible (Mathiassen et al., 2002).

The present study focused on reducing the occurrence of trunk inclination in those parts of the job where it was most pronounced, with the basic objective of decreasing the overall occurrence of trunk inclination in the job. If, instead, the occurrence and elimination of "peak" exposures *per se* were the focus of the assessment, a random sampling approach would not likely be an effective strategy (Paquet et al., 2005). Alternative exposure assessment strategies such as continuous long-term exposure assessment or measurements that target a particularly portion of the exposure distribution (e.g., those associated with a particular task suspected to include the peak) have been used effectively by others to document intervention effects in such cases (e.g., Mirka et al., 2003).

4.4. Generality of the results

One important limitation of the study is that the estimate of each worker's true exposure distribution is based on a small number of samples (cf. Fig. 2), and hence quite uncertain. However, the exactness of the estimated exposure distributions for each specific worker is only of secondary importance as they are used only to provide a realistic set of exposure data as a basis for simulation. In contrast, the estimates of sampling performance are, indeed, affected by the limited data set of 16 measurement units per worker, each covering about three minutes of work. In the simulation, each collected sample, both before and after the intervention, will appear to correctly reflect 1/16 of the total exposure distribution of that individual. In a real occupational setting, this is grossly optimistic, considering that exposure will vary even within each 1/16 of the overall job, and that a single video recording of about three minutes corresponds to only a minor fraction of the total working time. Consequently, performance of the investigated sampling strategies is even more critical in a real occupational setting than what appears from our results.

This notion of sampling performance probably being poorer in true practice than in our simulation is further substantiated by the fact that uncertainty following from intra- and inter-observer variability was not fully reflected in our data. If, for instance, the same sequence of work (i.e. the same video recording) was randomly selected to represent the job both before and after the intervention, the corresponding two exposure values were taken to be identical. In true practice, two sequences of work would be observed on two different occasions, which would – even if they were, in fact, identical – result in two different exposure estimates due to the inherent uncertainty associated with the observation *per se*. This methodological variability within and between observers, which adds to the true job exposure variability in deciding sampling performance, can probably be of a considerable magnitude (Kazmierczak et al., 2006), in particular in the practitioner's case where each work sample is typically observed only once by only one observer (Paquet et al., 2006).

These limitations, and the fact that the study concerns one specific manufacturing job assessed by a single exposure parameter, call for caution when transferring the results to interventions in other occupations evaluated by other biomechanical exposures. Larger studies that involve more workers, a range of occupational tasks and additional exposure metrics are needed for the development of sampling guidelines that can be broadly applied by ergonomics practitioners evaluating interventions. We do, however, emphasize the general message that sampling performance is a more critical concern than what appears to have been realized in general ergonomics practice and in many previous intervention studies published in the scientific literature. The risk of erroneously distrusting an intervention that is, in fact, effective is considerable unless a substantial effort is devoted to assessing pre- and post-intervention exposure.

This study took a practitioner's perspective by focusing on detecting intervention effects for single individuals. However, the generic issue of whether limited exposure sampling will be able to verify interventions that change the shape of possibly non-normal exposure distributions is pertinent also to the usual endeavor in research to document generalizable intervention effects at a group level. A particular intervention conducted in an occupational setting may well affect different individuals to different extents, thus changing the exposure distribution across individuals within a group. Since, in addition, sampling a limited number of individuals as a basis for judging intervention effects is usual in ergonomics research (Westgaard and Winkel, 1997; Mathiassen et al., 2002), we believe that the empirical approach for assessing sampling performance used in the present study could also be relevant even to investigations at a group level.

5. Conclusions

For interventions in self-paced manufacturing that lead to substantial reductions of trunk inclination in those parts of the job where it occurs the most, as few as three pre- and post-intervention exposure samples of ten work cycles each can be sufficient to reach a fair probability of detecting that the intervention has an effect at all on the overall occurrence of pronounced trunk inclination in the job for an individual worker. Larger samples are needed to reasonably estimate the magnitude of the intervention effect, even when it is substantial. For less effective interventions, limited exposure sampling can lead to very low probabilities of detecting that the intervention has an effect, let alone its correct size. Thus, in general ergonomics practice as well as in research, a large number of repeated samples per worker may be needed to arrive at a satisfactory level of credibility for any conclusion on the effects of an intervention targeting pronounced trunk inclination. The bootstrap-based simulation methods described in this paper can be used to estimate the necessary sample size in such cases, but additional studies are needed for the development of sampling guidelines that are generalizable across a variety of occupations and intervention effectiveness scenarios.

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