Assessment of physical work load in epidemiologic studies: common measurement metrics for exposure assessment

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There are many possible means of determining exposure ranging from self-reports of physical exposure to measures of muscle activations and estimated spinal loads. In epidemiologic studies, issues of validity make instrumented measures preferable, however issues of cost and practicability tend to force investigators to less costly but less valid and less reliable measures of exposure, such as self-report questionnaires. This paper presents a method by which estimates of exposure from self-report questionnaires, expert observers, work sampling, video analysis and electromyograms can be reported in a common metric, Newtons of force on a tissue, and show, as an example of its application, estimation of spinal compression on auto workers. A common metric allows a flexible approach to selection of measurement methods in occupational settings: no matter which instrument is used the results can be combined to provide an overall picture of exposure. This approach to exposure assessment for the low back allows for comparability across studies and settings.

1. Introduction

In epidemiologic studies of work and musculoskeletal health the issue of best quantifying exposure for large numbers of participants performing a wide range of jobs has come to the fore, notably in Stock (1991), Hagberg (1992), Wiktorin et al. (1993, 1996), Kerr et al. (1993), Kumar (1994), Winkel and Mathiassen (1994). Central to these proposals is the concept of a consistent ‘internal exposure’ or ‘dose’ within the body, suggested as being measured in a metric such as Newtons of force (Winkel and Mathiassen 1994). The optimal measure of exposure would have a number of characteristics defined: (1) the point within the body being considered; (2) the intensity or magnitude of the exposure; (3) the time variation of the exposure, and (4) the total duration of the exposure (Winkel and Mathiassen 1994, Hagberg et al. 1995). It is necessary to assess all these characteristics to properly define an individual’s ‘exposure’. The use of a ‘common metric’ (consistent measure) for exposure across different jobs is one approach to meeting the challenge presented by Winkel and Mathiassen (1994).

This paper presents a method by which estimates of exposure from self-report questionnaires, trained observers, work sampling, video analysis and electromyograms can be reported in a common metric, Newtons of force on a tissue, and show,
as an example of its application, estimation of spinal compression on automobile assembly workers.

2. Exposure assessment

Exposure to physical stressors has received increased scrutiny recently in an attempt to adapt the terms and concepts used in other branches of occupational epidemiology to the study of musculoskeletal disorders (Armstrong et al. 1993, Winkel and Mathiassen 1994, Hagberg et al. 1995). A major challenge is to develop exposure metrics that are related to musculoskeletal disorders, are relevant to occupational settings, and which are capable of flexible and cost effective application across a wide range of occupations and occupational settings. This is currently not done systematically and thus the completeness of many studies and the comparison of studies is rendered problematic (Winkel and Westgaard 1992). In addition, in epidemiologic studies, issues of validity make instrumented measures preferable. However, issues of cost and practicability tend to force investigators to less costly but less valid and less reliable measures of exposure such as self-report questionnaires. The use of the approach presented here could improve the process of comparability of studies as suggested by Leaman (1994).

Many studies of the relationship between work and musculoskeletal disorders have concentrated upon ‘stereotypic’ work tasks with short cycle times, most likely because of resource and time constraints. One of the more difficult challenges facing ergonomists and epidemiologists is to assess the more commonly occurring jobs with long cycle times or irregular work patterns. This often forces investigators to use different approaches and instruments for assessing these two extremes making comparability of data difficult or impossible.

There are many possible exposure measures ranging from job titles (classifications) and self-reports of physical exposure to direct measures of muscle activations and estimations of muscle loads (Hagberg et al. 1995). Typically, instrumented measures of physical stressors, which might be expected to be the best measures of current exposure, tend to be time consuming and expensive and many investigators have opted for questionnaire instruments instead. Self-reports from questionnaires have the advantage of being cheap to administer, while allowing for measures of a wide range of occupational and non-occupational risk factors both in current and past employment (Wiktorin et al. 1993, 1996). Unfortunately, the results of questionnaire validation studies often have not been encouraging (Buckle et al. 1986, Wiktorin et al. 1993). It appears that respondents can identify whether exposure to some stressor, such as vibration or lifting, has occurred but they do not give reliable information either on the nature or on the magnitude of the exposure (Wiktorin et al. 1993).

A single measurement method is unlikely to be feasible given the wide variety of occupational settings and purposes of the investigators. An alternative is to develop a framework that allows a combination of measurement methods to take advantage of the best features of each. This paper will develop such a framework for exposure assessment for low-back pain using, only as an example, a common metric of Newtons of spine compression. This facilitates comparisons between jobs and studies and also allows a ‘toolbox’ approach to selection of measurement methods in occupational settings. No matter which instrument is used, the results can be combined to provide an overall picture of low-back exposure in the same units of measurement.
There are many reported physical risk factors for low-back pain. Winkel and Mathiassen (1994) describe three categories of variables: physical (Garg 1989), individual, and psychosocial (Bongers 1993). Here physical exposure is the focus, yet even within this category measurement metrics include percent of time in given postures (%), maximum weight lifted (kg), maximum torso angle (degrees), spinal compression (N) and spinal shear (N).

In this paper, lumbar compression (N) will be used as a common metric across measurement methods. There is no intention to suggest the pre-eminence of compression as a single risk factor. However, spinal compression as an exposure measure does contain biomechanical justification and is, therefore, a reasonable example to present. It encompasses many of the reported risk factors uncovered by studies using questionnaire instruments such as non-neutral trunk postures and heavy lifting. Moreover, lumbar compression has been used extensively as a measure of exposure (Kumar 1990). In addition, Marras et al. (1993) report trunk moment to be a strong risk factor; lumbar compression is highly linearly related to trunk moment. While it is infrequent to see spinal motion unit failure associated with reported occupational low-back pain, high loading of the spine is almost inseparable from high loads on other spinal tissues such as muscle and ligament (McGill and Norman 1986).

Notwithstanding, the above rationale for using spinal compression (expressed in Newtons) as an exposure measure, it must be emphasized that this paper is intended to present a method by which exposure information can be obtained from a wide variety of methods; self-report questionnaires, expert observers, work sampling, video analysis and electromyograms. An example of how this approach has been used to structure exposure assessment in a large case-control study of risk factors for low-back pain in automobile workers will then be presented.

3. Estimation of spinal compression from disparate measurement methods

The primary problem in arriving at a common metric is to convert inputs from different measurement methods into estimates of exposure in the same units of measurement, in this case spinal compression in Newtons.

Five different methods were used to obtain input information. Five separate sources of data were used: postural and load information provided from a self-administered questionnaire, trained observers using a similar instrument, a posture and load sampling process by trained observers noting worker postures by selection from diagrams at random times during the work period (up to 3 h of observation), postural information taken from freeze frame video of the participant’s most stressful posture determined by the trained observers and EMG from erector spinae muscles normalized to spinal compression. A short description of each measurement method is presented later.

A biomechanical model of the lumbar spine was used as the core of all five exposure measure methods and therefore merits a brief description. The model is a quasi-dynamic, two-dimensional linked-segment model that comprises 15 segments. It is quasi-dynamic in the sense that inertial forces acting on the hands in lifts, lowers, pulls or pushes, rather than static load weights only, can be input if their magnitudes and directions are known. Body segment accelerations are not included, therefore the model is not completely dynamic. Asymmetric body postures can be input. Anthropometrics for segment masses and locations of mass centres for men and women are taken from Plagenhoef (1971) and Zatsiorsky and Seluyanov (1983) or can be input by the user. The participant’s body weight and gender must be specified. Postural
input is obtained from digitized x,y coordinates of body joints or via on-screen manipulation of a moveable manikin. The model calculates forces and moments at each joint starting at the wrist of each arm and proceeding to the elbow, shoulder, 7th cervical vertebra and down to L4/L5.

Compression and shear forces at L4/L5 are estimated from knowledge of the moment of force and reaction forces at this motion unit. A 6 cm moment arm length is used to represent the geometry of a single equivalent torso extensor ‘muscle’ for the estimation of the compression component. This moment arm length was incorporated as a result of findings from work with a fully dynamic, much more anatomically detailed, EMG-assisted model (McGill and Norman 1986; Potvin et al. 1991).

None of the spine models that have been presented to date in the literature have been directly validated by comparison of model estimates of muscle force, spinal compression or shear with direct measures of these variables in the same units of measurement. Technically this type of validation is currently not possible. Consequently anatomical and physiological content validity in the structure and function of these types of models is important. An attempt has to be made to incorporate as much content validity as possible, but assumptions and simplifications are present in all models. The impact of errors in model output estimates of compression are minimized in the example data presented in this paper since the same spine model was used to process input data from all methods described to provide an estimate of spinal compression.

4. Self-report questionnaire

The questionnaire asks respondents to identify their most demanding tasks and their relative durations, and for each task to identify common postures and loads (cf. Kumar 1990). Postures of the trunk and arms are chosen from a number of images and the force exerted is estimated. Software was used to create joint co-ordinates from the indicated postures. Each posture reported, combined with loading parameters, was then input into the biomechanical spine model to determine the lumbar moment of force and spine compression (Andrews et al. 1996). Time and frequency information were gathered to enable assessment of both peak and cumulative loading parameters. The same questions were also answered by trained observers and processed in the same manner. The worker also gave information on many other variables such as vibration and work rates. Of course, worker perception of work remains an important measure and variables such as perceived effort and pain were assessed as well using Borg-type scaling techniques (Andrews et al. 1996).

5. Posture and load sampling

Information on the distribution of low-back compression was also obtained from a work sampling approach. Although a number of similar schemes exist, for example, RULA (McAttamney and Corlett 1993, Keyserling 1986), OWAS (Karhu et al. 1977), they did not give output measures that could be converted to a lumbar compression metric and thus could not be used in this approach.

Postures of the back and arms, the load handled and the load direction were sampled for up to 3 h at mean intervals of 15 s to 1 min depending on the cycle time of the job. Once again, the aim was to obtain both postural information and the force data required to estimate low-back demands. The posture was classified into one of 13 back postures and the load was classified as being close, midway or far from the shoulder in the horizontal direction. Each combination of back posture, arm position,
load and load direction was input into a two- or three-dimensional biomechanical model, as appropriate, and a ‘look-up’ table of joint moments of force and estimates of spinal compression and shear for 50th percentile male or female created (Wells et al. 1995). The work sampling procedure was thus capable of estimating not only a distribution of postures adopted but also the peak load and the amplitude distribution of spinal loading produced by the task throughout the duration of the sampling period.

6. Trunk electromyography (EMG)

Erector spinae EMG recorded during work can be scaled to a standardized isometric reference contraction that is then used to produce a continuous estimate of lumbar compression from the EMG signal. This is a simplified version of an EMG processing approach to scale trunk electromyograms to spinal compression developed specifically for use in field settings (Wells et al. 1994). The original method, described by McGill and Norman (1986) and by Potvin and Norman (1993), uses as input a large number of sites of myoelectric activity and lumbar spine kinematics to scale and modulate the myoelectric activity to predict spinal load. The simplified technique has been shown to coincide acceptably with biomechanical model estimates of compression when presented in the form of an Amplitude Probability Distribution Function, APDF (Potvin et al. 1990, Mientjes 1996).

This study utilized recently available self-contained, portable EMG data collection units (Mega Electronics Inc; ME3000P) that can collect 4 channels of EMG for up to 2 h without downloading. The EMG data were collected bilaterally from the erector spinae muscles at the T9 and L3 levels. The EMG was sampled at 1000 Hz, averaged, and stored every 100 ms.

The normalization contraction was a standardized, slightly forward flexed trunk posture with a weight held in the hands. The load and posture resulted in a spinal compression of about 3000 N, close to the action limit (AL) as defined by NIOSH (1981). The resulting spinal compression was estimated by submitting the joint coordinates, obtained from a video analysis, the workers’ body weight and the magnitude and direction of the applied forces, to the biomechanical model described earlier (Neumann et al. 1995). The electromyograms recorded during work were downloaded from the datalogger and normalized by the contraction described above.

The time history of the normalized EMG was described as an Amplitude Probability Distribution Function (APDF) and reported as ‘compression normalized EMG’ in Newtons. The 10th, 50th, 90th and 99th percentiles were chosen to represent static, median and two estimates of peak loading (cf. Jonsson 1982).

The basic scheme for generating an exposure measure in a common metric of spinal compression from five different measurement methods is summarized in table 1.

7. Implementation of the common metric in a field study of risk factors for low-back pain in automotive assembly workers

The automotive assembly environment has many people engaged in well-defined tasks with cycle times typically of the order 1 to 5 min. Another large group is relief workers who perform dozens of tasks per day or work on repair and rework tasks. Approximately one-third of the employees are engaged in maintenance or other non-repetitive tasks. To illustrate the implementation of the previously described approach, its use in assessing the exposure of three different jobs in an automotive assembly plant is presented. An example of three types of jobs is presented in table 2.
Table 1. Obtaining a common metric of Newtons of low-back compression from different methods.

<table>
<thead>
<tr>
<th>Measurement method</th>
<th>Risk factors</th>
<th>Spinal compression estimated from</th>
</tr>
</thead>
<tbody>
<tr>
<td>Self-report questionnaire (includes diary)</td>
<td>Any risk factor, present and past</td>
<td>Reported posture, load and load direction.†</td>
</tr>
<tr>
<td>Expert observer checklist</td>
<td>Current and observable risk factors</td>
<td>Observed posture, load and load direction.†</td>
</tr>
<tr>
<td>Posture and load sampling</td>
<td>Observed load and posture</td>
<td>Sampled load, posture and load direction.†</td>
</tr>
<tr>
<td>Video with post hoc motion analysis</td>
<td>Video record of posture at a number of suspected peak load conditions</td>
<td>Digitized posture, load and load direction.†</td>
</tr>
<tr>
<td>EMG via belt-mounted data logger</td>
<td>Muscle activation from lumbar and thoracic musculature and resulting spinal load</td>
<td>Calibrated and processed EMG.‡</td>
</tr>
</tbody>
</table>

†Posture and load information input to a biomechanical model, see Andrews et al. 1996. ‡See Wells et al. (1994) for more details.

Table 2. Description of the three jobs used to illustrate the exposure assessment methods.

<table>
<thead>
<tr>
<th>Job type</th>
<th>Short-cycle job</th>
<th>Long-cycle job</th>
<th>Non-cyclic job</th>
</tr>
</thead>
<tbody>
<tr>
<td>Job title</td>
<td>Assembly operator</td>
<td>Paint repair operator</td>
<td>Materials handler</td>
</tr>
<tr>
<td>Cycle time</td>
<td>About 1 min</td>
<td>About 1 hour</td>
<td>Undefined but repeats most elements daily</td>
</tr>
<tr>
<td>Typical tasks</td>
<td>(1) Runs screws</td>
<td>(1) Remove plastic body parts</td>
<td>(1) Drive lift truck</td>
</tr>
<tr>
<td></td>
<td>(2) Pull wires</td>
<td>(2) Prepare</td>
<td>(2) Lift boxes</td>
</tr>
<tr>
<td></td>
<td>(3) Wait</td>
<td>(3) Sand</td>
<td>(3) Open boxes</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(4) Clean</td>
<td>(4) Drag empty pallets</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(5) Tape</td>
<td>(5) Wait</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(6) Wait</td>
<td></td>
</tr>
</tbody>
</table>

Table 3 summarizes the potential methods available for exposure assessment of each job. For more straightforward short cycle jobs (typically of a few seconds to a few minutes duration) there is a choice of a large number of instruments, from questionnaire to biomechanical models, to estimate both peak and cumulative demands. For longer cycle times, of the order of an hour, there still exist a number of instruments to determine peak loads as it is possible to follow workers for periods of up to a day using checklists and video as well as to record EMG on self-contained data loggers for this period. For very irregular jobs it is possible to assess peak
demands using video or checklists or posture sampling; however, cumulative demands are more problematic. The use of a diary or logbook becomes critical to determine the tasks and the approximate proportion of time spent in each of them.

Figure 1 shows how assessments can be structured. For the short cycle job (Job 1) any combination of the assessment methods can be used to obtain a relatively complete picture of the current exposure, often without the necessity of breaking the job down into tasks. For longer cycle jobs (Job 2), a task approach (breaking the job into tasks) becomes necessary; the exposure associated with each task must be measured. The exposure for the job can then be obtained by appropriate time weighting of the task exposures. Task breakdowns may be avoided if representative cycles can be observed and measured directly. For the irregular cycle job (Job 3), a task-based approach is imperative. The challenge then becomes to identify all relevant tasks and obtain a sample of them. If peak load is of interest then the performance or simulation of irregular yet stressful tasks is critical. If cumulative load or static load is of interest then seemingly low demand tasks, such as monitoring via visual display units, are important to capture.

Tables 4 and 5 show the benefits of the approach described; despite using a different measurement method for each job, it is still possible, in principle, to produce an exposure measure (in a common metric and units of Newtons) for comparison of peak and static load demands. Only one example estimate is provided in this paper although each method provides its own estimate of exposure. It is likely that each method has different accuracy and precision, and the estimates of spinal load will differ on the three example jobs. To avoid misleading impressions of the agreement between the different methods only a single value for each job will be presented at this time.

Table 4 presents a peak load from digitized video for the short-cycle job (Job 1), the peak load from posture and load sampling for Job 2 and the peak load from a self-report questionnaire for the irregular tasks (Job 3). Jobs 1 and 2 show similar peak demands while the materials handling job (Job 3) has considerably higher peak demands.

Table 5 illustrates two methods of obtaining static (continuous) loads for the three jobs. For static load (defined as the 10th percentile of the amplitude probability
Figure 1. Schematic of the integration of four assessment methods for three jobs with widely varying temporal characteristics.

Table 4. Example of exposure measures in the common metric (N) obtained for three different jobs using three different measurement approaches; peak load. The jobs are described in table 2.

<table>
<thead>
<tr>
<th>Exposure measurement method</th>
<th>Self-report</th>
<th>Posture and load sampling</th>
<th>Biomechanical model from video</th>
<th>Exposure in common metric, N peak</th>
</tr>
</thead>
<tbody>
<tr>
<td>Job 1</td>
<td>–</td>
<td>–</td>
<td>2029</td>
<td>2029</td>
</tr>
<tr>
<td>Job 2</td>
<td>–</td>
<td>2031</td>
<td>–</td>
<td>2031</td>
</tr>
<tr>
<td>Job 3</td>
<td>4797</td>
<td>–</td>
<td>–</td>
<td>4797</td>
</tr>
</tbody>
</table>
distribution function, APDF), processed trunk electromyography and posture and load sampling are possible methods. The long cycle job (Job 2) demonstrates the highest static loads, probably as a result of the long periods of time spent in a flexed trunk posture. The short cycle job (Job 1), demonstrates an almost upright trunk position, and as a result the static load is low; just above upper body weight.

The common metric approach presented should be contrasted to the more usual measures of exposure for the low back. Even for a given type of method, such as a questionnaire, the output metric is often different between investigators and even between job types studied (e.g. office versus construction workers). For example, in different questionnaires, repetitiveness may be quantified by the number of lifts or the number of trunk flexions; these are quite different estimates of exposure. Similarly, across different occupational settings, risk factors for low-back pain in office environments may be recorded as the percentage of time spent in a chair without contact with a lumbar support whereas in a construction setting, the risk factor is more likely to be the percent of time in trunk flexion. This makes comparisons between studies and between different job types difficult.

It must be acknowledged that while the exposure estimates presented in this paper may share a common metric, the accuracy and precision offered by each is probably very different. The direct (instrumented) methods will probably give more precise estimates of current exposure, and therefore better estimates of risk, Burdorf (1995). To assess this, a comparison of the estimates produced by each method (intermethod comparison, Burdorf 1995) is underway as part of a large epidemiologic study in automobile workers (Wells et al. 1993). The objective of this paper was to demonstrate that a common exposure metric is feasible from several disparate measurement methods.

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References


